WPD Virtual Statcom WP4 report

For: Western Power Distribution

Prepared by: Grant McCormick (Senior Consultant)

Client Reference: NIA_WPD_37
PSC Reference: JK7261-TR-04-03
Revision: 03
Date: 26th May, 2020

Document History

Revision	Date	Description of changes
00	10/04/20	First issue to WPD for revision
01	30/04/20	Second issue to WPD
02	14/05/20	Final Issue to WPD
03	26/05/20	Final Revision approved by WPD

Revision	Date	Author	Peer Review	Approved
00	10/04/20	Grant McCormick	David Mills	David Mills
01	30/04/20	Grant McCormick	David Mills	David Mills
02	14/05/20	Grant McCormick	David Mills	David Mills
03	26/05/20	Grant McCormick	David Mills	David Mills

Pure Offices, Lakeview House, Wilton Drive, Warwick CV34 6RG, United Kingdom

P: +44 1926 675 851 W: https://www.pscconsulting.com

Executive Summary

Political and social forces in the UK are driving the change towards clean low carbon technologies such as renewable generation. As renewable distributed generators (DGs) are becoming integrated into existing electricity networks, technical constraints arise that can limit the total amount of generation or load a network can host. The Virtual Statcom project is an innovation project that seeks to investigate the technical feasibility of increasing the network hosting capacity, for both generation and load, by optimising the reactive power dispatch of DGs.

As part of this investigation two main algorithms have been developed. The first is an algorithm to determine the generation and load hosting capacity of a network and the second is an algorithm to optimise the reactive power dispatch of existing generators with the aim to increase hosting capacity. This report presents algorithms that have been updated to be able to optimise generation on a feeder group basis, depending on the whether the feeder group is constrained by thermal loading limits or bus voltage limits. The optimisation of generation was previously undertaken at a network level.

Hosting simulation studies have been undertaken for extreme operating conditions and time series cases based on historic load and generation profiles. The following WPD networks, selected for different network characteristics, have been used for the hosting simulations:

- Barnstable 33 kV BSP
- Pyworthy and North Tawton 33 kV BSP
- Tiverton 33 kV BSP
- Tiverton Moorhayes 11 kV Primary

Studies and analysis identified the following key findings:

- The Virtual Statcom released some generation capacity however this capacity benefit is very small and depends on the network topology and assets. Therefore, the Virtual Statcom solution would need to be combined with other interventions to increase the generation capacity benefits provided.
- The Virtual Statcom algorithm has released load capacity. Minimising the thermal loading objective function provided a post optimisation increase in load hosting capacity for almost all network configurations, system generation and load profiles.
- There is a clear need to determine the constraint for a network at the feeder group level so that any optimisation can focus on the specific thermal loading or voltage constraint. A future real-time implementation would need to continuously estimate the changing network constraints, in order to ensure that the limiting constraint is identified.
- Due to the network complexities and interaction between different feeder groups minimising the objective function does not always provide a post optimisation increase in generation hosting capacity for all network configurations, system generation and load profiles.

The key findings show than it is worthwhile to determine how the Virtual Statcom concept can be used as a tool in real time and system planning timeframes for network management.

Table of Contents

Table of Abbreviations

Abbreviation	Term
DG	Distributed Generator
FPL	Flexible Power link
LTDS	Long Term Development Statement (Nov 2018)
MW	Megawatts, unit for real power
Mvar	Mega volt-amperes reactive, unit for reactive power
NIA	Network Innovation Allowance
NOP	Normally open point
OPF	Optimal power flow
ORPD	Optimal reactive power dispatch
p.u.	Per unit
pf	Power Factor
PSC	Power Systems Consultants UK Ltd
PSS/E	Power System Simulator for Engineering
Python	A high-level, general-purpose programming language
RPF	Reverse power flow
SCADA	Supervisory Control and Data Acquisition
Statcom	Static Synchronous Compensator
UKPN	United Kingdom Power Networks
VBA	Visual Basic for Applications
WP	Work Package
WPD	Western Power Distribution

1. Introduction

1.1. Introduction to Project

Western Power Distribution (WPD) has engaged Power Systems Consultants UK Ltd. (PSC) to deliver an innovation project known as the Virtual Statcom, the project is being run by WPD and funded under the Ofgem, Network Innovation Allowance (NIA).

As an increasing number of distributed generators (DGs) connect to distribution networks, technical constraints arise that can limit the total amount of generation a network can host. To overcome the technical constraints associated with distributed generators and continue to operate a safe, secure and reliable network, WPD undertake traditional network reinforcements as well as initiating and leading innovation projects to develop new solutions. A key focus of innovation projects is to increase the utilisation of existing assets to defer network reinforcements, the Virtual Statcom project fits in this category of project.

The objective of the Virtual Statcom project is to determine the technical feasibility of increasing the network hosting capacity, for both generation and load, through implementing an algorithm to control and coordinate the reactive power output of existing generators in the distribution network.

If the project demonstrates benefit it will enable more generation and load to be connected to the distribution network without the need for network reinforcement.

The project is structured into the following 5 main work packages (WP):

- WP1 - Data gathering/validation and study zone selection.
- WP2 - Power flow simulations & Virtual Statcom algorithms.
- WP3 - Graphical User Interface.
- WP4 - Time series comparison studies.
- WP5 - Virtual Statcom feasibility study reporting.

The work packages are being delivered in order except WP3 and WP4 which are being delivered in parallel.

1.2. Introduction to this Report

This report details the work completed in delivering WP4.

- Section 2 provides background to the project and explains the motivation and concept of the project.
- Section 3 presents the motivation behind the feeder group approach that was implemented based on the learning gained in the previous Work Packages.
- Section 4 and Section 5 detail the modifications to the hosting and optimisation algorithms to implement a feeder group approach, including the feeder group weighting calculation.

- Section 6 presents the updated generation and load hosting results for the extreme operation conditions.
- Section 7 presents the generation and load hosting capacity results based on historic generation and load profiles.
- Section 8 provides analysis of the feeder group approach.
- Section 9 presents the conclusions and recommendations from WP4.

1.3. Western Power Distribution Networks Assessed

The Virtual Statcom project focuses on WPD's Southwest region model. The network model has 42 Bulk Supply Points (BSPs) and eight Primary substations that have been modelled as part of the WPD's Network Equilibrium project. The following list presents the three BSPs and one Primary selected as study networks for the Virtual Statcom project. Figure 1-1 shows the location of the study networks in WPD's southwest region. For more detail on the networks selected networks refer to the WP1 report [1].

- 33 kV Bulk Supply Point networks:
  - Barnstaple
  - Pyworthy and North Tawton
  - Tiverton
- 11 kV Primary Networks:
  - Tiverton Moorhayes Primary

Figure 1-1 - Location of study networks

2. Virtual Statcom Project Background

2.1. Passive Distribution Networks

The design of traditional distribution networks was based on a top down passive approach. In these traditional distribution systems, the primary function was to transfer power from the transmission system level Grid Supply Points (GSPs) to the Bulk Supply Points (BSPs) and onwards to primary substations and the end consumers of electricity. A key characteristic of passive distribution networks is that power flows were always considered in a single direction, notably from a higher voltage sources towards lower voltage loads.

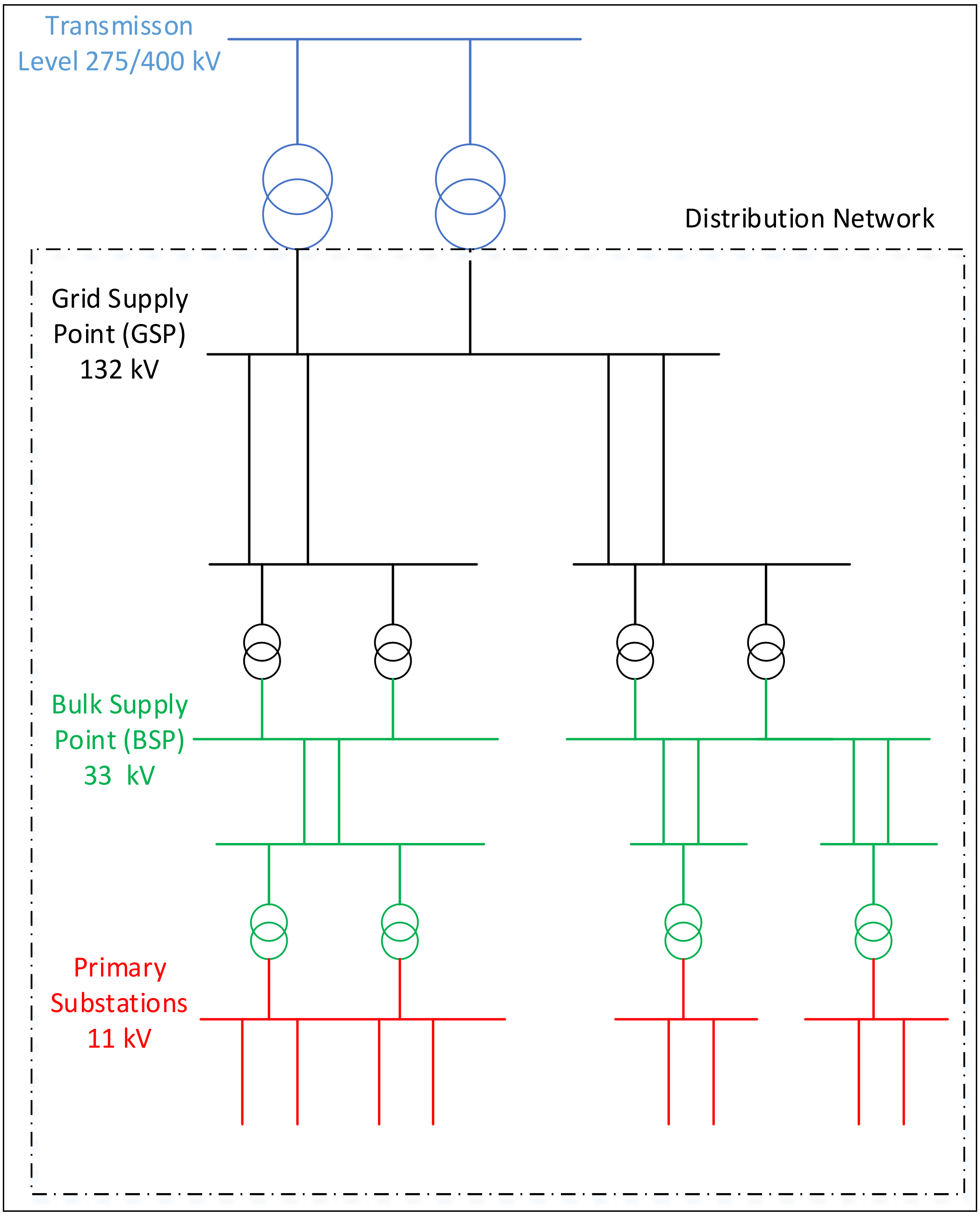


Figure 2-1 - Distribution Network layout

2.2. Accommodating Distribution Connected Generation

The past 10-20 years has seen an increase in generators connected to distribution networks, known as Distributed Generators (DGs). In WPD's South West network DGs predominantly consist of renewable generation (i.e. wind, solar) connected at 33 kV and 11 kV voltage levels. The increase of DGs changes the key characteristic of passive distribution networks. Power will now flow in either direction and is dictated by changing loads and generation which can be intermittent in nature.

The uptake of DGs provides benefits of low carbon energy. Initially, it can also help relieve network thermal constraints by supplying power closer to the load centres. This can therefore reduce loadings on upstream lines, cables and transformers. However, distribution networks cannot accommodate ever increasing connections of DGs. Aside from the practical considerations such as land availability and favourable sites for wind or solar irradiance, technical factors will constrain the total amount of DGs that can be connected.

A terminology used to quantify how much generation a network can accommodate is "hosting capacity" [2] [3]. The Hosting Capacity of a network is defined as the total amount of distributed generation that the network can accommodate without violating predefined operational, physical and statutory limits.

The technical factors that can constrain the hosting capacity of a network include:

- Voltage regulation
- Voltage step constraints
- Thermal ratings
- Fault levels
- Power quality

The impact of these technical factors on hosting capacity is briefly explained in this section.

2.2.1. Voltage Regulation

The statutory voltage limits for distribution networks in the UK are set in the Electricity Safety, Quality and Continuity Regulations 2002 and are +/- 6% of the nominal voltage at 11 kV and 33 kV. These statutory voltage limits will be incorporated in to the Virtual Statcom project.

The traditional method of voltage regulation in passive distribution networks is to increase the bus voltage at BSPs and primary substations above the 33kV and 11 kV nominal ratings to account for the voltage drop along the distribution feeders and ensure that far end of feeders are within the statutory limits. However, the situation changes if DGs are connected along the feeders or at the end of feeder. The connection of DGs can lead to voltage rise issues. This is due to the voltage at the point of connection of a DG being proportional to the real and reactive power of DG and load [4]. For combinations of load and generation, when load is less than generation a voltage rise takes places at the DGs point of connection. With traditional voltage regulation and DG, bus voltages along the feeder can exceed the +6% statutory voltage limit. It is for this reason that DGs are typically required to operate with a leading power factor (importing reactive power) to counter this voltage rise.

The voltage head room on a feeder limits the size of individual DGs and therefore the hosting capacity for the network. The voltage head room on a feeder is defined as the difference between the upper statutory voltage limit and the bus voltage at a given bus. To illustrate voltage head room, consider the following two bus example where:

- The bus voltage at the BSP is fixed at 1.0 p.u.
- The reactive power of the load and generator are ignored.
- 3 arbitrary scenarios are considered:
    - When the real power of the generator is less than the load. (Pg < Pd)
    - When the real power of the generator is equal to the load. (Pg =Pd)
    - When the real power of the generator is greater than the load. (Pg > Pd)

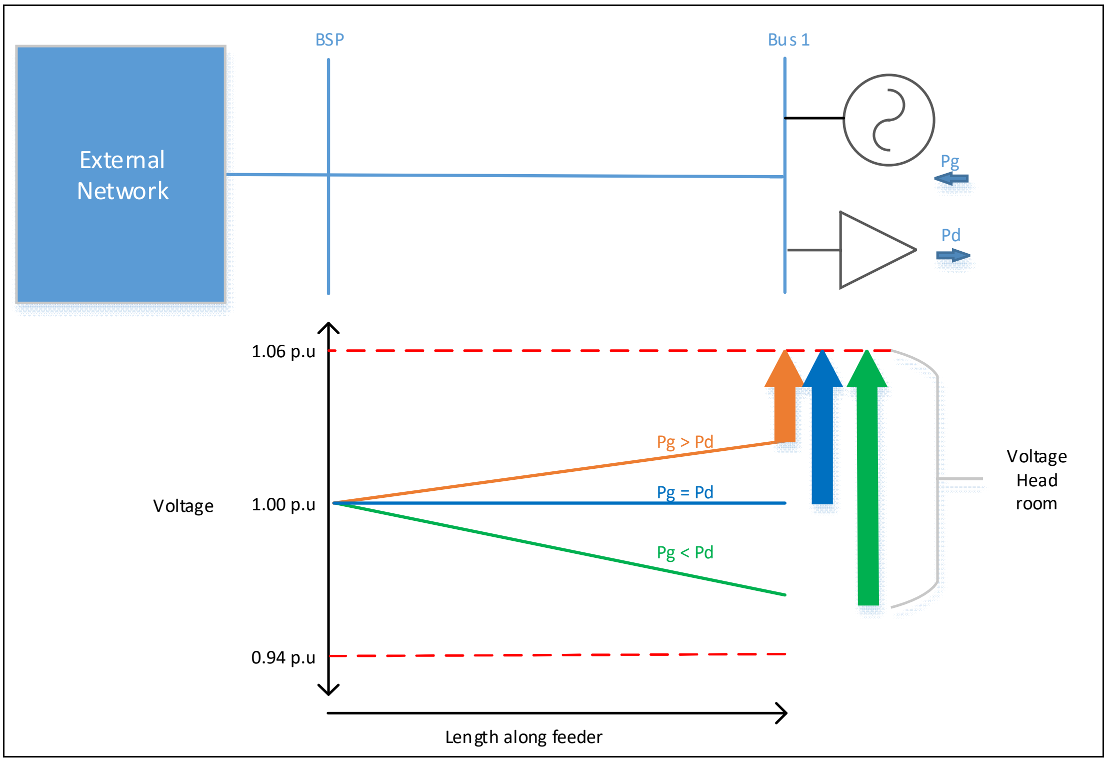


Figure 2-2 - Voltage head room

Figure 2-2 demonstrates that as the amount of real power from the generator (Pg) increases the voltage head room decreases.

2.2.2. Voltage Step Constraints

The hosting capacity may also be constrained by voltage step constraints. The voltage step constraints for distribution networks in the UK are set in the Distribution Planning and Connection Code and Engineering Recommendation P28. The voltage step constraints are +/- 3 % for frequently occurring events. The tripping of a DG can cause voltage steps in either direction depending on the size of the DG and system conditions, this can also limit the size of DG on a feeder and hence hosting capacity. These voltage step constraints are incorporated in to the Virtual Statcom project.

2.2.3. Thermal Ratings

The installation of DGs in networks can be beneficial and can reduce the loading of lines, cables and transformers. However, as the total distributed generation installed increases, reverse power flows arise which can exceed the thermal ratings of connected equipment. Therefore, the hosting capacity can be limited by the thermal ratings of equipment. Further to this, some equipment such as transformer tap changers and circuit breakers have lower ratings under reverse power conditions limiting the hosting capacity even further.

2.2.4. Fault Levels

A distribution system is designed to safely handle a certain level of short circuit current. In passive distribution networks the short circuit current infeed was assumed to come from the upstream network. However, by adding distributed generation, this condition changes as the distributed generators will also contribute fault current. This can lead to the short circuit capacity of the distribution network being exceeded thus limiting the hosting capacity. Specific issues associated with fault levels are not part of the scope of this project and are not considered in the Virtual Statcom Project.

2.2.5. Power Quality

Increasing DG connections has to potential affect voltage and current quality in the grid. The proliferation of power electronic based devices is expected to introduce impacts including; harmonic distortion (both characteristic and low order non-characteristic); rapid voltage changes; unbalance due to single phase connections; and long-term voltage variation and transients due to the connection and disconnection of various DG sources. Specific issues associated with power quality are not part of the scope of this project and are not considered in the Virtual Statcom Project.

2.3. Techniques to Increase Hosting Capacity

The traditional means to increase hosting capacity is to undertake network reinforcements - this can be costly and time consuming. Alternative means to increase hosting capacity include:

- Voltage control schemes to control transformer set points and switched capacitors.
- Reactive power or power factor regulation.

2.4. Virtual Statcom Concept

The existing DGs connected to WPD's BSPs and Primary networks operate with a fixed power factor between unity and 0.95 leading (import reactive power) and this may not be appropriate for all network conditions. This is the fundamental area that the Virtual Statcom project aims to investigate. The concept of the Virtual Statcom assumes that instead of operating with fixed power factor, the DGs can operate across a power factor range. By optimising the reactive power output of DGs in a network for different conditions through perhaps a new flexibility service, there is potential to increase the hosting capacity.

3. Virtual Statcom Feeder Group Approach

3.1. Defining Feeder Groups

A feeder group is defined in this report and project as the branches and buses in a radial feeder or parallel feeders from a BSP/Primary bus or buses. Figure 3-1 presents an example for WPD's Tiverton 33 kV BSP network with 5 different feeder groups identified. Appendix A shows the defined feeder groups for the projects other study networks Barnstaple 33 kV BSP, and Pyworthy and North Tawton 33 kV BSP. Feeder groups are identified for Tiverton Moorhayes 11 kV network but are not able to be shown concisely on its single line diagram. An algorithm has been developed to define the feeder groups for use in the Virtual Statcom algorithms and is detailed in Appendix B, Feeder Group 0 is always defined as the BSP or Primary bus bar connected to the network supply transformer(s).

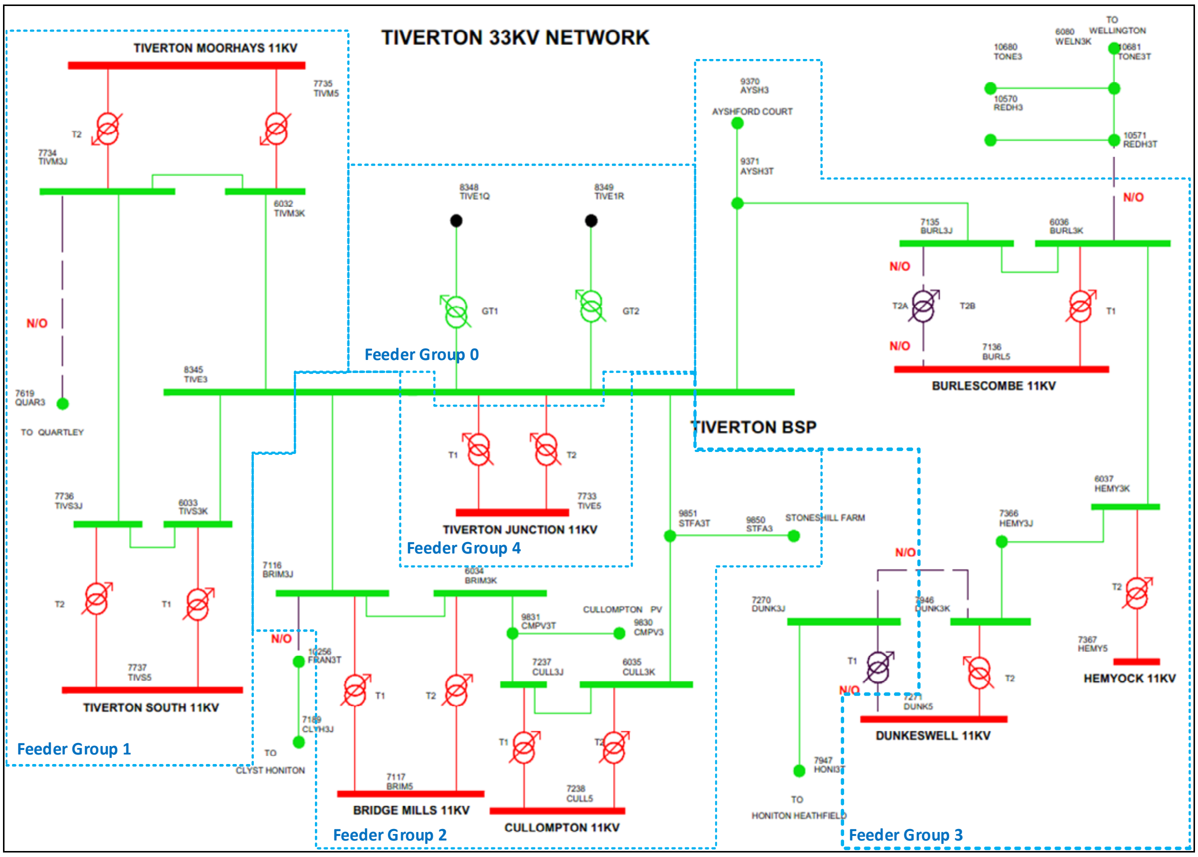


Figure 3-1 - Tiverton 33 kV BSP Feeder Groups

3.2. Motivation for the Feeder Group Approach

This section provides a summary of the WP2 findings and conclusions to explain the motivation behind the feeder group approach in the Virtual Statcom project.

3.2.1. Summary of Work Package (WP2) Findings

The objective of the Virtual Statcom algorithm is to maximise generation or load hosting capacity by changing the reactive power output of existing network generators. In Work Package 1 it was identified that it is possible to define an objective function that maximises the hosting capacity calculated from a hosting capacity algorithm directly. However, this type of objective function was discounted in WP1 in favour of objective functions that aim to maximise hosting capacity indirectly through maximising the available headroom for generation or load [1]. Defining the objective function to maximise the output of the hosting capacity algorithms was discounted as during the particle swarm optimisation process the objective function needs to be evaluated multiple times for every particle, and as the hosting capacity algorithm is calculated iteratively, this places a high burden on computational resources and would result in long solving times.

The Virtual Statcom optimisation algorithm developed in WP2 [5] has the primary aim of resolving network constraints by optimising the reactive dispatch of existing generators. If the algorithm is able to resolve the network constraints, or if no network constraints exist in a study case, the secondary aim of the algorithm is to increase headroom for new generation or load to connect to the network.

The optimisation algorithm was initially configured with objective functions to determine a reactive power dispatch for existing generators, that either reduced thermal loading on circuits or reduced network voltages to provide headroom for generation. Analysis of the optimised reactive power dispatch showed that the optimisation to reduce thermal loading or optimisation to reduce voltages did not increase generation hosting capacity in all network configurations [5]. The analysis identified that the two objective functions were conflicting, in that reducing system voltages results in higher thermal loading and reducing thermal loading results in higher voltages. As a result of this, a modified optimisation algorithm trialled an objective function using a fixed weighting factor with the aim of obtaining a balance between thermal and voltage headroom to increase generation hosting capacity.

The network's generation hosting capacity results using a reactive power dispatch determined by fixed weighting factor optimisation also did not provide capacity increases in all network configurations. Analysis of the weighting factor showed that optimisation using a fixed weighting factor does not balance the voltage and thermal headroom in a network during all conditions. This suggested that an optimum weighting factor is dependent on the contingency configuration and sensitive to the generation and load scenarios.

Power system analysis on PSS/E cases with optimised reactive power set points and after the generation hosting algorithm had been run was undertaken. It showed that by using manual reactive dispatch in two contingency configurations, an increase in generation hosting capacity could be achieved if certain feeders groups had been optimised separately to reduce voltages or thermal loading [5]. This showed that within a study network that some feeders groups are thermally constrained whereas others are voltage constrained.

3.2.2. Work Package 2 (WP2) Conclusions

The findings from WP2 summarised in Section 3.2.1, provided the following conclusions:

1. Optimising to reduce voltages or optimising to reduce thermal loading does not produce generation hosting capacity benefits in all network configurations.
2. A fixed weighting factor does not successfully achieve a balance between voltage and thermal headroom for all network configurations. Therefore, a method to calculate a weighting factor was required.
3. Feeder groups are either thermally or voltage constrained when increasing generation. Therefore, to assess the weighting factor objective function the Virtual Statcom optimisation algorithm needed to be able to:
    a. Determine which feeder groups become thermally constrained and which feeder groups become voltage constrained when increasing generation.
    b. Optimise the reactive power of existing generator in a feeder group dependant on the voltage and thermal characteristics of the feeder group.

4. Feeder Group Approach - Network Capacity Algorithms

4.1. Study Networks with Initial Network Constraints

The capacity hosting algorithms developed in WP2 were designed not to scale any load or generation if thermal or voltage violation(s) exist in the initial system model. In PSS/E cases with initial violation(s) where the Virtual Statcom algorithm resolved the violation(s), the post optimisation hosting capacity showed unrealistic levels of increase as it was being compared to the generation hosting capacity of zero pre-optimisation.

The hosting algorithms methodology has been updated for PSS/E cases with initial violations. The updated algorithm does not scale generation or load in a feeder group with an initial violation but will scale generation/load in the remaining feeder groups as long as the initial violations do not become worse – i.e. no higher than the initial violation(s). Figure 4-1 shows the implemented generation or load hosting per contingency algorithm.

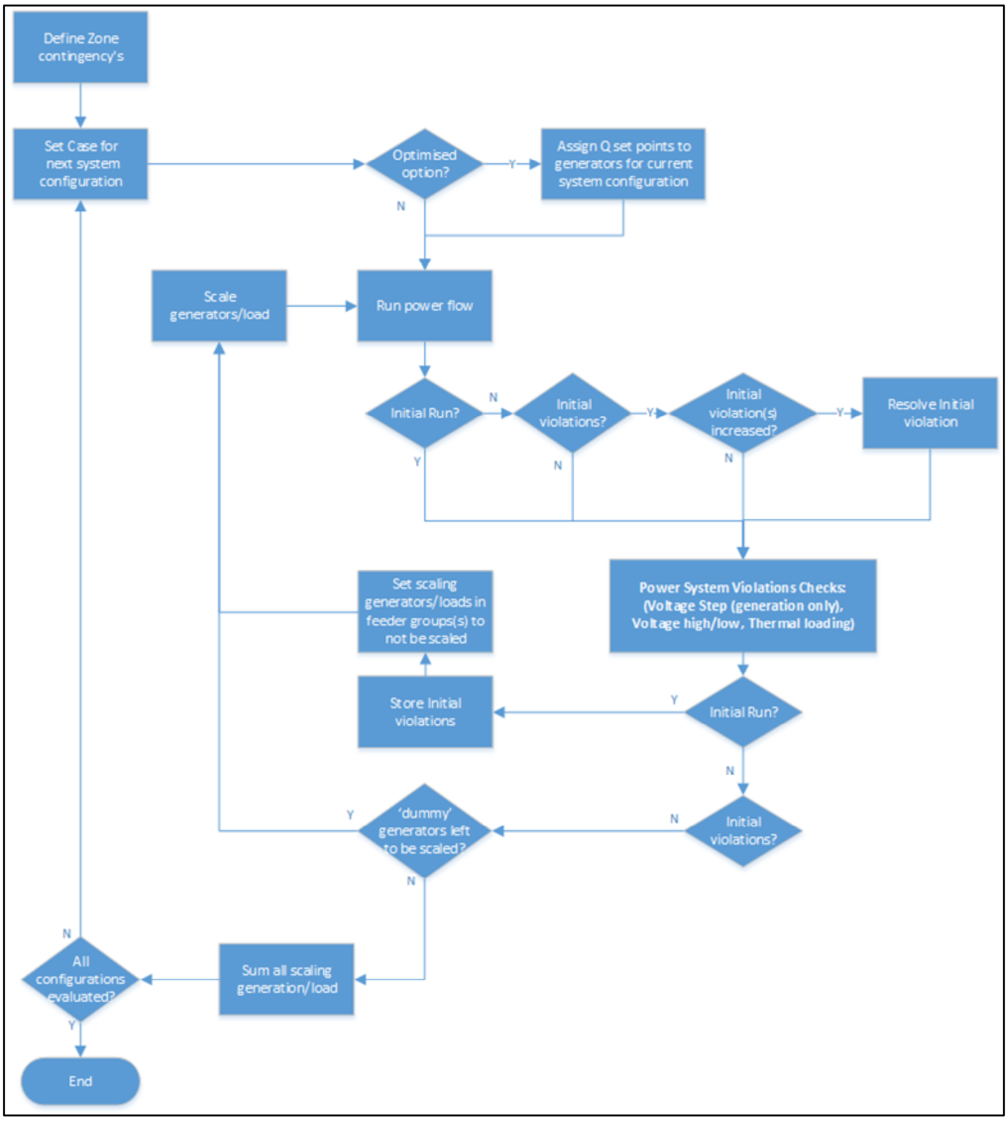


Figure 4-1 - Generation or Load Hosting per contingency algorithm process

4.2. Feeder Group Generation / Load Scaling

The capacity hosting algorithms developed in WP2 scaled each dummy generator or load based on a predefined real power scaling increment. The algorithms have been updated to scale generators or loads at a feeder group level. The default is to scale generation and load in 1 MW steps per feeder group. The 1 MW is divided by the number of generators and load being scaled at each scaling iteration. When scaling loads the real power of feeder groups loads are scaled by 1 MW and then the reactive power is scaled according to the each loads original power factor.

A new function has been developed to reduce the number of 1 MW feeder group step sizes required to reach the first study network violation. This reduces the computational time of the hosting algorithm, especially in cases with low initial levels of generation or load. The algorithm increases the generation/load in large MW steps initially to identify the first study network violation and then determines the starting point for the 1 MW per feeder group scaling. Details of the initial dynamic scaling function is provided in Appendix B.

4.3. Transformer Tap Changing Action

The results provided in WP2 were calculated with all transformers tapping. To determine if the hosting capacity increases are solely the result of the change in reactive power dispatch rather than tap changer action, the hosting capacity algorithms were modified to lock all transformer taps in the study network when increasing generation or load.

From initial time series study results, the hosting algorithm provided counter intuitive results, in that the generation hosting capacity of a network was reducing as load was increasing. Analysis of the studies with transformer taps locked showed that; in some network configurations, the generation hosting capacity was becoming limited by the 11 kV bus voltages. The assumption to lock the tap changers meant the 11 kV bus voltages were no longer being controlled by the 33/11 kV Primary supply transformers automatic voltage regulation. This was particularly evident in cases with high load and low generation.

Figure 4-2 shows 33 kV bus voltages, 11 kV bus voltages, branch loadings and dummy generation output during the generation hosting algorithm using fixed taps for a contingency of the Tiverton BSP 132/33 kV transformer G2. The black dotted boxes in Figure 4-2 highlights that the 11 kV voltages are limiting the generation hosting on the network to 13.5 MW. Figure 4-3 shows the comparison for the same contingency configuration with the 33/11 kV supply transformers using automatic voltage regulation and shows the reverse power rating of the remaining 132/33 kV transformer becomes the limiting factor at 93 MW.

The analysis detailed above led to the hosting capacity algorithm being modified to lock the taps of the BSP 132/33 kV or Primary 33/11 kV tie transformers only, when evaluating generation and load hosting capacity. Tie transformers are the transformers that provide a connection between Grid Supply Point (GSP) networks and a BSP network and between a BSP network and a Primary network. A tap change of tie transformers causes voltage steps for every bus connected to the lower voltage bus, this can increase or decrease the networks generation hosting capacity.

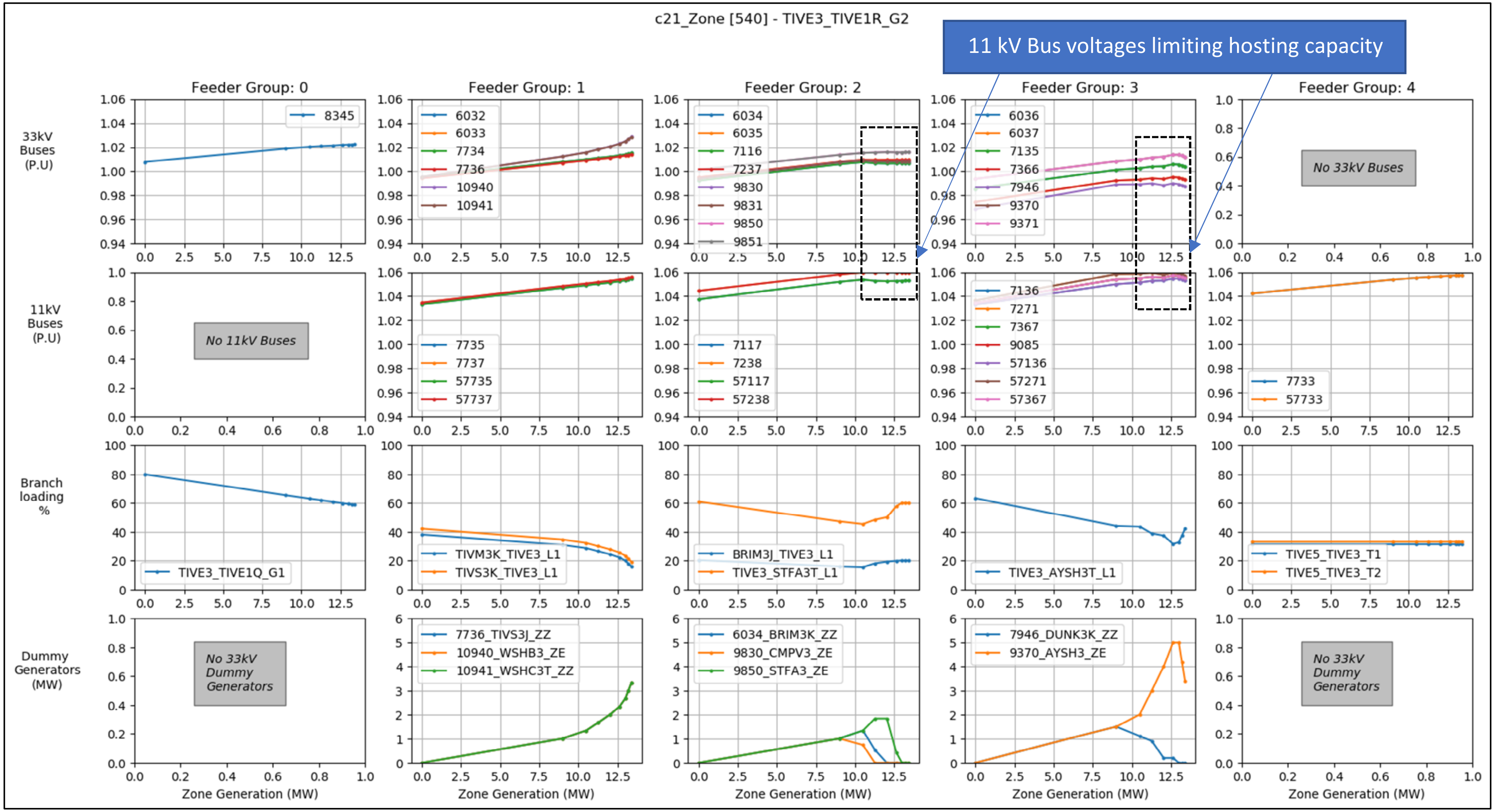


Figure 4-2 - Generation hosting algorithm for a contingency of Tiverton 132/33 kV transformer with fixed taps

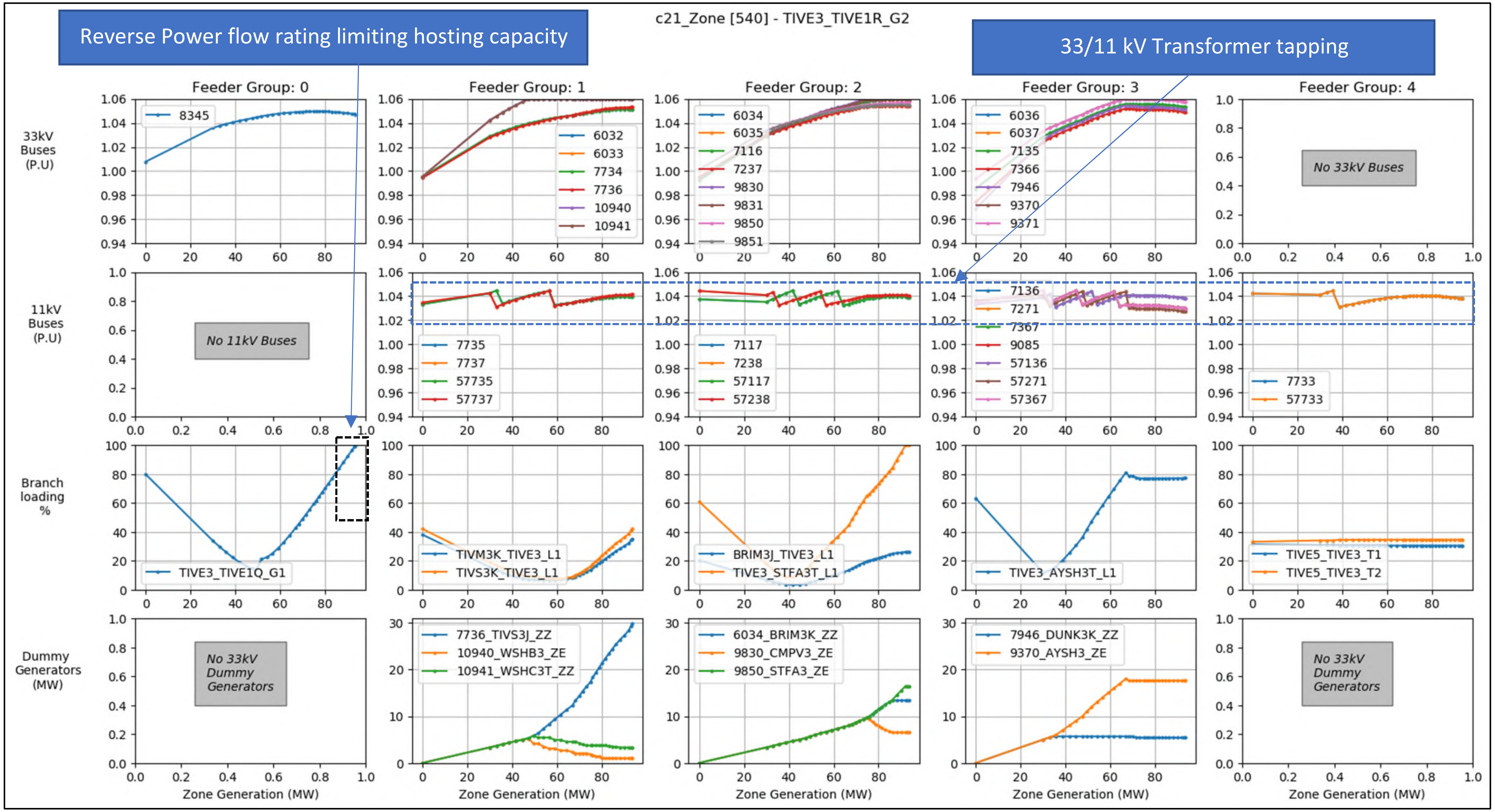


Figure 4-3 - Generation hosting algorithm for a contingency of Tiverton 132/33 kV transformer with tie transformers taps

4.4. Method to Resolve Transformer Reverse Power Flow (RPF) Violations

When running the hosting algorithms, if a transformer Reverse Power Flow (RPF) violation is identified, the generation being scaled up in the study network will be scaled back to resolve the violation and stop being scaled. The approach implemented in the hosting algorithm developed in WP2 used the same method to resolved circuit loadings violations and transformer RPF violations. This resulted in the transformer not always being loaded at 100% when the algorithm ended due to the scaling back step size used.

A new method has been implemented where an initial coarse step size is used and then a finer step size to resolve transformer RPF violation. If a RPF violation is detected, the algorithm calculates and reduces generation by an initial coarse step size, then a finer step size to bring the loading to less than 100%.

5. Feeder Group Approach - Optimisation Algorithm

When optimising the reactive power dispatch to increase generation hosting capacity, the algorithm developed in WP2 implemented the following optimisation options:

a) Reduce system voltages.

b) Reduce the thermal loading on circuits.

c) Fixed weighting factor attempt to balance between voltage and losses.

Option c) was implemented as the optimisation performed in option a) and b) are conflicting when increasing network generation, in that reducing system voltages results in higher thermal loading and reducing thermal loading results in higher voltages. Analysis undertaken in WP2 [5] and summarised in Section 3.2.1 showed that a method to calculate a weighting factor for each feeder group was required to assess the weighting factor objective function.

This section contains the details of the implemented calculation to determine a weighting factor per feeder group and the modifications to the weighting factor objective function. These enabled the use of feeder group weightings when performing optimisation to increase network hosting capacity.

5.1. Weighting Factor Optimisation Methodology

As part of this work, a method was required to develop an objective function that could use calculated feeder group weighting factors to determine how much focus should be given towards optimising for voltage or reducing thermal losses for each feeder group during the optimisation process. The aim of developing the objective function to use calculated weighting factors was to have an objective function that could dynamically calculate feeder group weighting factors for a given network configuration and generation and load conditions.

The method used to calculate feeder group weighting factors is based on determining the thermal and voltage sensitivity of a feeder group for increases in generation. This method is used to develop an independent objective function that can be applied to a PSS/E case. The weighting factor objective function's goal is to increase the amount of real power that can be added to a feeder group before a thermal or voltage constraint occurs, therefore increasing the headroom and hosting capacity.

The methodology used to evaluate the weighting factor objective function is the same as with the reducing thermal loadings and reducing network voltage objective functions. Where the objective function optimisation is applied to the initial PSS/E case and the hosting capacity algorithm is used to evaluate whether the objective function has successfully created an increase in a network hosting capacity.

5.2. Feeder Group Weighting Factors

5.2.1. Calculating Weighting Factors when Increasing Network Generation

The implemented feeder group weighting calculation is based on increasing generation slightly and then estimating whether a feeder group will become voltage or thermally constrained first. The calculation approach assumes that the system voltages and thermal loading change linearly with increases in generation.

The following process is followed to determine a weighting factor per feeder group:

1. Identify feeder groups in network (Figure 3-1)
2. For each feeder group:
    a. Calculate the initial voltages for every busbar in feeder group and initial loading of the branches (circuits or transformers) connecting to the central busbar.
    b. Add generation to every busbar at the generation scaling level (33 kV for BSP networks and 11 kV for Primary Networks).
    c. Increase each total feeder group generation by 10% or 1.0 MW, whichever is greatest.
    d. Calculate the new voltages for every busbar in feeder group and new loading of the branches (circuits or transformers) connecting to the central busbar.
    e. Apply Equation 1 to calculate weighting factor (λ).

Equation 1:
$$\lambda = \frac{\Delta \mathrm{T}}{\Delta V}$$

Where:

Equation 2:
$$\Delta T = \frac{100\% - T_{initial}}{T_{after} - T_{initial}}$$

Equation 3:
$$\Delta \mathrm{V} = \frac{1.06 - V_{initial}}{V_{after} - V_{initial}}$$

Where:

$T_{initial}$ – Initial loading on a branch (circuit or transformer)

T_{after} - Loading on a branch (circuit or transformer) after generation increase.

$V_{initial}$ – Initial busbar voltage

V_{after} - Busbar voltage after generation increase

ΔT and ΔV determines the number of times the generation can be increased by the same amount in MW before a thermal limit is breached. ΔV determines the number of times the generation can be increased by the same amount in MW before a voltage limit is breached. Equation 1 then determines the ratio between the voltage and thermal limit being breached. If λ is less than 1.0 the feeder group is thermally limited, if λ is greater than 1.0 the feeder group is voltage limited.

When determining the increase in generation, the limiting circuit for each feeder group will be the branch which connects the feeder group to the BSP/Primary substation. Therefore, when determining the thermal loading of the branches and whether this will become the limiting factor only those branches are considered. In the case of busbars, all experience an increase as a result of a generator connected anywhere on the feeder and therefore have to be considered. Only voltages at the generation scaling level (33 kV or 11 kV) are considered though as it is assumed that the downstream transformers will maintain the lower voltage level within acceptable limits.

5.2.1.1. Feeder Group Weighting Example

Table 5-1 shows the calculated weighting factor for each of the feeder groups in the Tiverton 33 kV BSP network in the intact system configuration for the minimum load, maximum generation scenarios. A mark-up of the Tiverton's feeder groups is shown in Figure 3-1.

Table 5-1 - Calculated Weighting factors for Tiverton

Feeder Group	Busbars	Weighting Factor	Comment
0	[8345, 83451, 83452]	0.124	Thermal limited due to reverse power flow of grid transformers. Very little voltage impact
1	[6032, 6033, 7734, 7735, 7736, 7737, 10940, 10941, 57735, 57737]	1.493	Voltage limited with some thermal impact
2	[6034, 6035, 7116, 7117, 7237, 7238, 9830, 9831, 9850, 9851, 57117, 57238]	0.276	Thermal limited with very little voltage impact
3	[6036, 6037, 7135, 7136, 7271, 7366, 7367, 7946, 9085, 9370, 9371, 57136, 57271, 57367]	0.469	Thermal limited but with some voltage impact
4	[7733, 57733]	1.0	No busbars for generators to be connected so 1.0 assumed

Figure 5-1 and Figure 5-2 show the effect of generation increasing in each feeder groups 1 and 2 which are voltage and thermally constrained respectively. The weighting factor for feeder group 1 is greater than 1.0 and therefore this feeder group is expected to hit a voltage limit before it reaches a thermal limit. Figure 5-1 shows the busbar voltages and circuit loading during the generation increases in the feeder. The results support this showing that busbars 10940 and 10941 exceed the 1.06 p.u. limit whilst the TIVM3K_TIVE3_L1 and TIVS3K_TIVE3_L1 circuits are only loaded at 65%, shown by the black dotted line in Figure 5-1.

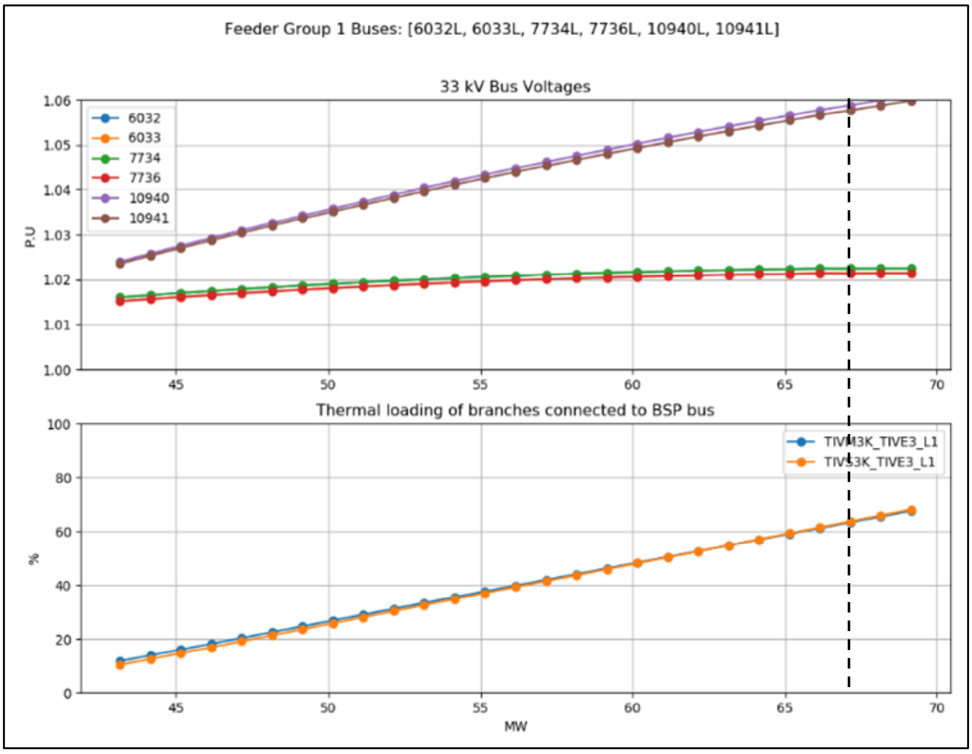


Figure 5-1 - Tiverton BSP 33 kV feeder group 1 with increasing generation

Feeder group 2 has a weighting factor which is less than 1.0 which means that the feeder group is more sensitivity to thermal loading of its circuits than the voltage at its busbars. Figure 5-2 supports this showing that with increasing generation the thermal loading of branch TIVE3_STFA3T_L1 exceeds 100% while the maximum bus voltage is only at 1.03 p.u, shown by the black dotted line in Figure 5-2.

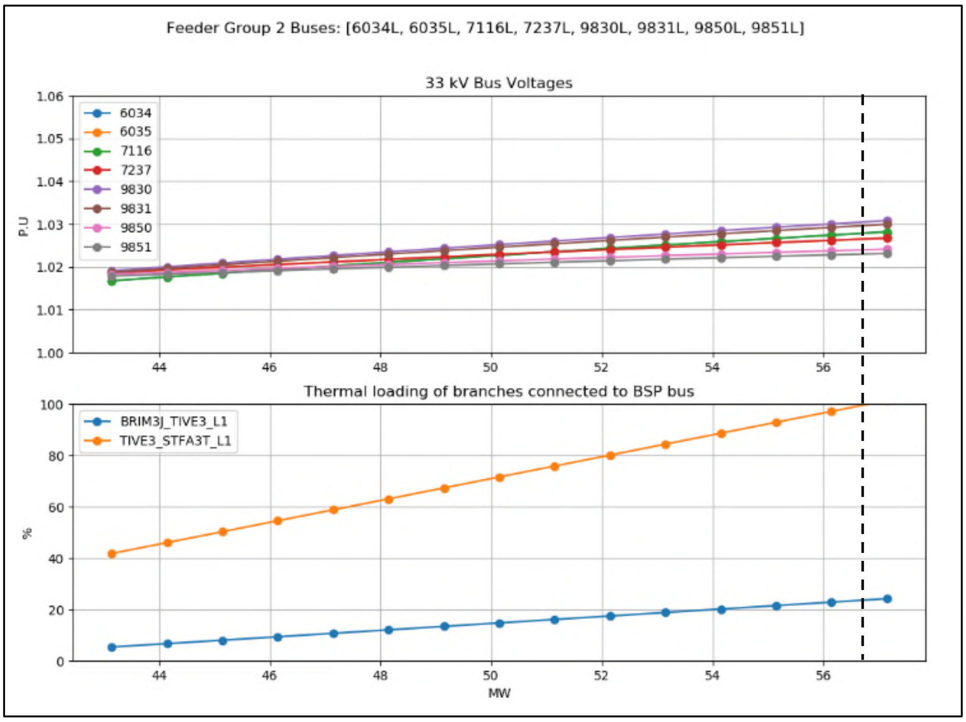


Figure 5-2 - Tiverton BSP 33 kV feeder group 2 with increasing generation

5.2.2. Feeder Group Weightings for Load Hosting

When increasing network loads bus voltages across the network decrease. When optimising to increase load hosting capacity the Virtual Statcom optimises to reduce the thermal loading on circuits, this results in raising network voltages and providing extra headroom for load. As a result, there is no need to determine a feeder group weighting factor when optimising to increase the load hosting capacity.

5.3. Objection Function

The objective function has been modified to use feeder group weighting factors. The modified objective function is optimised using the particle swarm optimisation (PSO) algorithm to determine reactive power set-points for existing generation. The following process is used to determine optimised reactive power set-points for each generator. The PSO algorithm implemented as part of the Virtual Statcom is initialised with 200 particles in the solution space, where 1 particle contains a set of reactive power dispatch values for all generators being considered:

1. Apply set-points for particle
2. Check voltages and thermal flows are within limits otherwise $P_{valid} = False$
3. For each feeder group:
    a. Determine average voltage for busbars in feeder group within allowable range using Equation 4

Equation 4:

$$\mathrm{V}_p = mean\left(\frac{V_{updated} - V_{lower\_limit}}{V_{upper\_limit} - V_{lower\_limit}}\right)$$

    b. Determine average reactive power flow for branches and transformers supplying feeder group within assumed power factor range (+/- 0.9)[1]

Equation 5:

$$Q_p = mean\left(\frac{Q_{updated} - Q_{lower\_limit}}{Q_{upper\_limit} - Q_{lower\_limit}}\right)$$

    c. Determine if valid particle using Equation 6

Equation 6:

$$P_{valid} = \begin{cases} \frac{V_p}{V_0} < 1.0, & if\ \lambda_{fg} > 1.0 \\ \frac{Q_p}{Q_0} < 1.0, & if\ \lambda_{fg} < 1.0 \end{cases}$$

    d. Calculate result using Equation 7:

[1] Based on MVA loading of branch / transformer

Equation 7 :
$$\alpha_{P_{fg}} = \begin{cases} V_p + (2 - \lambda_{fg}) \cdot Q_p, & if\ \lambda_{fg} > 1.0 \\ Q_p + \lambda_{fg} \cdot V_p, & if\ \lambda_{fg} < 1.0 \end{cases}$$

e. Determine whether increase or reduction from initial condition and return optimised value for this feeder group. i.e. $\beta_{0_{fg}}$ initially = 1.0 for each feeder group.

Equation 8:
$$\beta_{P_{fg}} = \frac{\alpha_{P_{fg}}}{\alpha_{0_{fg}}}$$

4. Calculate the overall optimised value for this particle using Equation 9

Equation 9:
$$\gamma_p = \sum \beta_P$$

5. Move onto next particle until γ_p is minimised with a change of <0.01.

Where:

V_p – Mean busbar voltage linearized between upper (1.06 p.u.) and lower (0.94 p.u.) voltage limits

Q_p – Mean branch reactive power flow linearized between upper and lower branch reactive power limits based on a power factor of 0.9 and initial branch MW flow

P_{valid} – Whether particle is valid and only valid particles are considered in the particle swarm algorithm

$\alpha_{P_{fg}}$ – Voltage and thermal factor for the feeder group taking into consideration the feeder group weighting

$\beta_{P_{fg}}$- Feeder group overall optimisation factor compared with original value

γ_p- Overall particle optimisation value

5.4. Reactive Power Available to Optimisation Algorithm

A future Virtual Statcom flexibility service would require that connected generation in WPD's networks have the operational capability to export or import reactive power rather than operate at a fixed power factor. To determine if there is a benefit to generation and load hosting capacity of connected generators operating in this manner, this project assumes that the existing generators in the PSS/E models can operate across a reactive power range. This reactive power range does not reflect existing generators reactive power capabilities or modifications to existing generators to provide a reactive power range, which is outside the scope of this project.

The optimisation algorithm developed in WP2 focused on the minimum load, maximum generation scenario for generation hosting and the maximum load, 10% generation scenario for load hosting. The assumption used to determine the reactive power range for each existing generator that is available to the Virtual Statcom in WP2, was based on the real power output of the generator with fixed power factor of 0.95 leading and 0.95 lagging as shown in Figure 5-3 a). A consequence of this assumption is that in the maximum load, 10% generation scenario very little reactive power is available to the Virtual

Statcom and this resulted in either inconclusive or very minor benefits when determining load hosting capacity.

To ascertain if there are any benefits for scenarios with low generation, the reactive power allocation assumption has been modified to provide a larger reactive power range for all real power outputs. Figure 5-3Figure 5-3 b) shows the modified reactive power range allocated to each existing generator in the optimisation algorithm. The reactive power available at maximum real power with power factor of +/- 0.95 is available across each generator's real power range.

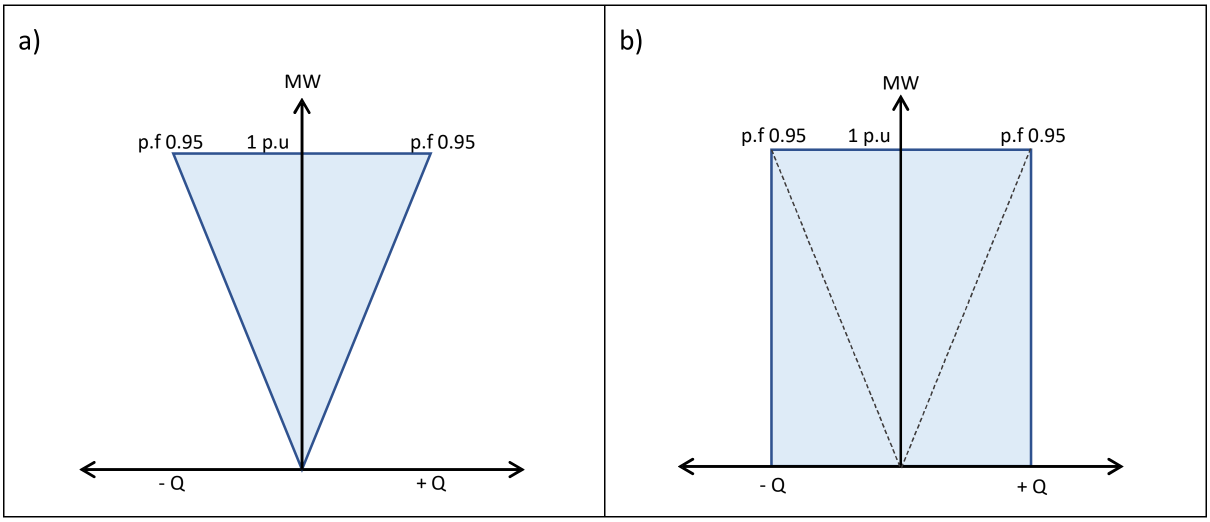


Figure 5-3 - Reactive power allocation assumption

6. Feeder Group Approach Results

6.1. Summary of Capacity Benefits Results

This section presents a summary of the generation and load hosting capacity results for Tiverton 33 kV BSP network, Barnstaple 33 kV BSP, Pyworthy and North Tawton 33 kV BSP and Tiverton Moorhayes 11 kV Primary. The detailed hosting results for each network are included in Appendix C.

The generation hosting summary results compare the following optimisation options for the minimum load, maximum generation scenario for the intact system and worst contingency configuration.

a) Thermal for each feeder group

b) Voltage for each feeder group

c) Calculated weighting factor for each feeder group

The load hosting summary results compare the optimisation to reduce thermal loadings for the maximum load 10% generation scenario and intact system worst contingency configuration.

The technical assumptions for the studies undertaken are included in Appendix F. The results in this section are coloured to show increases in green, decreases in red and no change in yellow.

6.1.1. Tiverton 33 kV BSP – Generation

Table 6-1 shows the generation hosting capacity in the Tiverton 33 kV BSP network, pre and post optimisation of reactive power set points, for the minimum load maximum generation scenario. The Virtual Statcom has limited benefit in this network region due to the reverse power flow limits of the BSP infeed transformers. The calculated weighting factor optimisation provides a small benefit in both cases in Table 6-1.

Table 6-1: Generation hosting capacity increase in Tiverton 33 kV BSP

Network: Tiverton 33 kV BSP Load/Generation Scenario: Minimum Load Maximum Generation							
Network Configuration	Pre-optimisation generation hosting capacity	Capacity Increase (MW)			Capacity Increase %		
		Thermal	Voltage	Calculated Weighting Factor	Thermal	Voltage	Calculated Weighting Factor
intact system	103.44	-22.82	-0.82	0.66	-22.1%	-0.8%	0.6%
TIVE3_TIVE1R_G2	59.35	1.03	-0.90	0.75	1.7%	-1.5%	1.3%

6.1.2. Tiverton 33 kV BSP – Load

Table 6-2 shows the load hosting capacity in the Tiverton 33 kV BSP network, pre and post optimisation of reactive power set points, for the maximum load 10 % generation scenario. For both the intact system and worst contingency there is a large benefit. The benefit presented here is greater than the load hosting results presented in WP2 report [5], this is a result of the modified assumption for the reactive power available from existing generators at low generation levels, described in Section 5.4.

Table 6-2: Load hosting capacity increase in Tiverton 33 kV BSP

Network: Tiverton 33 kV BSP Load/Generation Scenario: Maximum Load 10 % Generation			
Network Configuration	Pre-optimisation load hosting capacity	Capacity Increase (MW)	Capacity Increase %
intact system	77.87	11.57	14.9%
CULL3K_STFA3T_L1+ TIVE3_STFA3T_L1+ STFA3_STFA3T_L1	49.47	18.70	37.8%

6.1.3. Barnstaple 33 kV BSP – Generation

Table 6-3 shows the generation hosting capacity available in the Barnstable 33 kV BSP network pre and post optimisation of reactive power set points. The Virtual Statcom cannot resolve all violations in the worst contingency configurations for the minimum load, maximum generation scenario.

Table 6-3: Generation hosting capacity increase in Barnstable 33 kV BSP

Network: Barnstable 33 kV BSP Load/Generation Scenario: Minimum Load Maximum Generation							
Network Configuration	Pre-optimisation generation hosting capacity	Capacity Increase (MW)			Capacity Increase %		
		Thermal	Voltage	Calculated Weighting Factor	Thermal	Voltage	Calculated Weighting Factor
intact system	130.03	0.91	-1.29	1.23	0.7%	-1.0%	0.9%
SMOL3K_KING3T_L1+ BAST3_KING3T_L1+ KING3_KING3T_L1	55.42	0.00	0.00	0.00	0.0%	0.0%	0.0%

6.1.4. Barnstaple 33 kV BSP – Load

Table 6-4 shows the load hosting capacity in the Barnstable 33 kV BSP network pre and post optimisation of reactive power set points, in the maximum load, 10 % generation. For both the intact system and worst contingency there is a large benefit. The benefit presented here is greater than the load hosting results presented in WP2 report [5], this is a result of the modified assumption for the reactive power available from existing generators at low generation levels, described in Section 5.4.

Table 6-4: Load hosting capacity increase in Barnstable 33 kV BSP

Network: Barnstaple 33 kV BSP Load/Generation Scenario: Maximum Load 10% Generation			
Network Configuration	Pre-optimisation load hosting capacity	Capacity Increase (MW)	Capacity Increase %
intact system	53.98	18.24	34%
BAST1Q_BAST3_G1	48.38	16.10	33%

6.1.5. Pyworthy and North Tawton 33 kV BSP – Generation

Table 6-5 shows the generation hosting capacity available in the Pyworthy and North Tawton 33 kV BSP network, pre and post optimisation of reactive power set points, for the minimum load, maximum generation scenario. For the intact system, after optimising reactive power using all methods does not provide benefit. In worst contingency case, there are initial voltage and thermal violations in the same feeder group (Feeder Group 1) of the study network. The Virtual Statcom cannot resolve all violations caused in this case, therefore no generation can be added.

Table 6-5: Generation hosting increase in Pyworthy and North Tawton 33 kV BSP

Network: Pyworthy and North Tawton 33 kV BSP Load/Generation Scenario: Minimum Load Maximum Generation							
Network Configuration	Pre-optimisation generation hosting capacity	Capacity Increase (MW)			Capacity Increase %		
		Thermal	Voltage	Calculated Weighting Factor	Thermal	Voltage	Calculated Weighting Factor
intact system	244.36	-7.36	-19.70	-30.33	-3.0%	-8.1%	-12.4%
NTAW1_NTAW3_G1	146.91	0.00	0.00	0.00	0.0%	0.0%	0.0%

6.1.6. Pyworthy and North Tawton 33 kV BSP – Load

Table 6-6 shows the additional load hosting capacity available in the Pyworthy and North Tawton 33 kV BSP network pre and post optimisation of reactive power set points, in the maximum load, 10 % generation scenario. For both the intact system and worst contingency there is a significant benefit. The benefit presented here is greater than the load hosting results presented in WP2 report [5], this is a result of the modified assumption for the reactive power available from existing generators at low generation levels, described in Section 5.4

Table 6-6: Load hosting capacity increase in Pyworthy and North Tawton 33 kV BSP

Network: Pyworthy and North Tawton 33 kV BSPs Load/Generation Scenario: Maximum Load 10% Generation			
Network Configuration	Pre-optimisation Load hosting capacity	Capacity Increase (MW)	Capacity Increase %
intact system	125.91	32.40	26%
NTAW1_NTAW3_G1	88.00	23.33	27%

6.1.7. Tiverton Moorhayes 11 kV Primary – Generation

Table 6-7 shows the generation hosting capacity available in the Tiverton Moorhayes 11 kV Primary network pre and post optimisation of reactive power set points. The Virtual Statcom has relatively limited potential in this network region due to the small levels of reactive power available from the 2 generators in the network.

Table 6-7: Generation hosting capacity increase in Tiverton Moorhayes 11 kV BSP

Network: Tiverton Moorhayes 11 kV BSP Load/Generation Scenario: Minimum Load Maximum Generation							
Network Configuration	Pre-optimisation generation hosting capacity	Capacity Increase (MW)			Capacity Increase %		
		Thermal	Voltage	Calculated Weighting Factor	Thermal	Voltage	Calculated Weighting Factor
intact system	22.98	0.07	0.00	0.06	0.3%	0.0%	0.3%
TIVM3J__T1	12.37	0.12	0.00	0.00	0.9%	0.0%	0.0%

6.1.8. Tiverton Moorhayes 11 kV Primary – Load

Table 6-8 shows the additional load hosting capacity available in the Tiverton Moorhayes 11 kV BSP network pre and post optimisation of reactive power set points, in the maximum load, 10 % generation scenario. The Virtual Statcom has limited benefit in this network region due to the small levels of reactive power available from the 2 generators in the network.

Table 6-8: Load hosting capacity increase in Tiverton Moorhayes 11 kV BSP

Network: Tiverton Moorhayes 11 kV BSP Load/Generation Scenario: Maximum Load 10% Generation			
Network Configuration	Pre-optimisation load hosting capacity	Capacity Increase (MW)	Capacity Increase %
Intact system	11.37	0.00	0%
7735_95167_1	5.92	0.00	0%

6.2. Analysis of Generation Hosting Results

The generation hosting capacity results presented in this section show that no one method of optimisation produces a benefit under all system condition and configurations. There are cases where the automatic feeder group weighting factor provided benefit in some configurations but not all cases and in some cases did not achieve the same benefit from a voltage or thermal optimisation method. It should be noted that the results presented are due to assumption that full generator reactive power capability is available from existing generators at low generation levels as detailed in Section 5.4. Further discussion/analysis of the feeder group weighting optimisation method is provided in Section 8.

Pure Offices, Lakeview House, Wilton Drive, Warwick CV34 6RG, United Kingdom

P: +44 1926 675 851 W: https://www.pscconsulting.com

6.3. Analysis of Load Hosting Results

The load hosting capacity results presented in this section show that by optimising reactive power set points to reducing thermal loadings in a network produces a benefit under all system conditions and configurations. It should be noted that these benefits are due to assumption that full generator reactive power capability is available from existing generators at low generation levels as detailed in Section 5.4.

7. Time Series Studies

7.1. Purpose of Time Series Studies

The results presented so far in the Virtual Statcom project have been calculated using the edge case scenarios. The Virtual Statcom algorithms were developed focusing on the minimum load, maximum generation scenario for generation hosting and the maximum load, 10% generation scenario for load hosting. The purpose of the time series studies was to test the Virtual Statcom algorithms under different load and generation scenarios and analyse if any trends were apparent.

7.2. Time Series Functionality

Time series functionality has been added to the Virtual Statcom algorithms. At a high level, the time series functionality allows the optimisation and per contingency hosting algorithms to be run for multiple load and generation scenarios. The following details the process of how the time series studies are performed after a network zone to study has been selected.

1. Import time series generation and load data.
2. User selects time series period and time step-size.
3. User selects contingency configurations.
4. Run time series studies using hosting and optimisation algorithms.

The following section details the importing of time series data.

7.2.1. Import Generation and Load Data

Historic load and generation data from WPD's Supervisory Control and Data Acquisition (SCADA) system was provided to the project. In WP1 the historic data was validated, transformed and mapping rules developed to enable the SCADA data to be imported into PSS/E. The following procedure is used to import time series data:

1. Load the mapping rules for a network.
2. Identify the time periods the historical SCADA data covers.
3. Cleanse missing time series data
   - 3.1. If there is no SCADA data available for a generator then it is populated based on a typical data that is in included as part of the Virtual Statcom scripts and scaled to represent the size of the missing generator. In these studies, this is based on a typical solar generation curve obtained from analysing measurements from other generators.
   - 3.2. If SCADA data is available for a generation or load but is missing a particular timestep then those values are populated from the next closest day at the same time that contains a valid measurement.
4. Map the load and generation to the PSS/E case.

7.3. Time Series Study Details

The computational burden when performing time series studies using the Virtual Statcom is high and must be considered when undertaking time series analysis. As a result, week-long periods were selected from 4 seasons for the time series studies covering all study networks with 3-hour time steps. Additionally, a more detailed time series study was performed for Tiverton 33 kV BSP covering 1 day in 1 hour time steps. The historic data available to the project was from 2018 and is detailed in WP1 report [1]. Table 7-1 details the time series study periods and resulting number of study scenarios.

Table 7-1 - Time series study periods

Network(s)	Season	Study Period	Time Step	Study cases per network
Tiverton 33 kV BSP, Barnstaple 33 kV BSP Pyworthy and North Tawton 33 kV BSP, Tiverton Moorhayes 11 kV Primary	Spring	9th April 2018 – 15th April 2018	3 hours	48
	Summer	9th July 2018 – 15th July 2018		
	Autumn	8th October 2018 – 14th October 2018		
	Winter	8th January 2018 – 14th January 2018		
Tiverton 33 kV BSP	Autumn	10th October 2018	1 hour	24

7.3.1. Time Series Contingency Configuration Selection

To limit the number of contingency configurations for the time series studies; for each network the intact system (normal operating configuration), best and worst contingency configurations were selected. To determine the best and worst contingency the capacity hosting algorithm was used to determine the configurations with the lowest and highest generation/load hosting capacity. Table 7-2 and Table 7-3 show the contingency configurations studied for the generation and load time series studies for each study network.

Table 7-2 - Contingency Configurations for Generation Hosting Time Series Studies

Study Network	Type	Description	Contingency configuration name
Tiverton 33kV	Intact System	The normal operating configuration of the study network.	n/a
	Best	A contingency of the tee'd generator (WSHB) connected to Tiverton Moorhayes 33 kV substation	TIVM3J_WSHC3T_L1+ WSHB3_WSHC3T_L1
	Worst	A contingency of Tiverton 132/33 kV BSP transformer (G2).	TIVE3_TIVE1R_G2
Barnstaple 33kV BSP	Intact System	The normal operating configuration of the study network.	n/a
	Best	A contingency of the voltage regulator	SMOL3K_BATS3R_R1

		between South Moulton and Batsworthy Windfarm substations.	
	Worst	A contingency of the circuit between Heddon Cross and Barnstaple 33 kV substations.	HEDX3J_BAST3_L1
Pyworthy and North Tawton 33kV BSP	Intact System	The normal operating configuration of the study zones. (i.e. with the BSPs in parallel).	n/a
	Best	A contingency of the radial feeder from Stratton 33 kV substation.	CLOV3K_FORE3T_L1+ ESLA3T_FORE3T_L2+ FORE3_FORE3T_L2+ MORW3_MORW3T_L1+ MORW3T_STRA3_L1+ MORW3T_ESLA3T_L1+ ESLA3_ESLA3T_L1
	Worst	A contingency of North Tawton 132/33 kV BSP transformer (G1).	NTAW1_NTAW3_G1
Tiverton Moorhayes 11kV Primary	Intact System	The normal operating configuration of the study network.	n/a
	Best	The radial feeder from Tiverton Moorhayes 11 kV substation to Bus 95000	7735_95000_1
	Worst	A contingency of Tiverton Moorhayes 33/11 kV BSP transformer (T1).	TIVM3J__T1

Table 7-3 - Contingency Configurations for Load Hosting Time Series Studies

Study Network	Type	Description	Contingency configuration name
Tiverton 33kV	Intact System	The normal operating configuration of the study network.	n/a
	Best	A contingency of the circuit between Burlescombe and Hemyock 33 kV substations.	BURL3K_HEMY3K_L1
	Worst	A contingency of the circuit between Tiverton and Cullompton 33 kV substations.	CULL3K_STFA3T_L1+ TIVE3_STFA3T_L1+ STFA3_STFA3T_L1
Barnstaple 33kV BSP	Intact System	The normal operating configuration of the study network.	n/a
	Best	A contingency of the radial feeder from Barnstaple to Great Torrington 33 kV substation	TORR3K_DARM3T_L1+ DARM3_DARM3T_L1+ DARM3T_KNOK3T_L1+

			BAST3_KNOK3T_L1+ KNOK3_KNOK3T_L1
	Worst	A contingency of Barnstaple 132/33 kV BSP transformer (G1).	BAST1Q_BAST3_G1
Pyworthy and North Tawton 33kV BSP	Intact System	The normal operating configuration of the study zones. (i.e. with the BSPs in parallel).	n/a
	Best	A contingency of the radial feeder from Pyworthy to Launceston 33 kV substation.	LAUN3K_HNBF3T_L2+ ECUR3_HNBF3T_L2+ HNBF3_HNBF3T_L1
	Worst	A contingency of the North Tawton 132/33 kV BSP transformer (G1).	NTAW1_NTAW3_G1
Tiverton Moorhayes 11kV Primary	Intact System	The normal operating configuration of the study network.	n/a
	Best	The radial feeder from Tiverton Moorhayes 11 kV substation to Bus 95911	7735_95911_1
	Worst	A contingency of Tiverton Moorhayes 33/11 kV BSP transformer (T1).	TIVM3J__T1

7.4. Detailed Day Results

This section presents the generation hosting time series results for Tiverton 33 kV BSP network for a single day period. The time series results presented here compare the following optimisation methods:

a) Optimise to reduce thermal loading in each feeder group

b) Optimise to reduce bus voltages in each feeder group

c) Optimise based on calculated weighting factor for each feeder group

This analysis was carried out for the worst contingency configuration; An outage of the 132/33 kV Transformer G2 (TIVE3_TIVE1R_G2).

7.4.1. Optimising to Reduce Thermal Loading in the Network

Figure 7-1 shows time series results for Tiverton 33 kV BSP network with a contingency of the 132/32 kV Transformer G2 and optimising to reduce the thermal loading in the network. The results show that by optimising to reduce thermal loading the resultant reactive dispatch allowed for at least the same amount or an increase in the post optimisation capacity for 15 out of the 24 time series cases studied (62.5%).

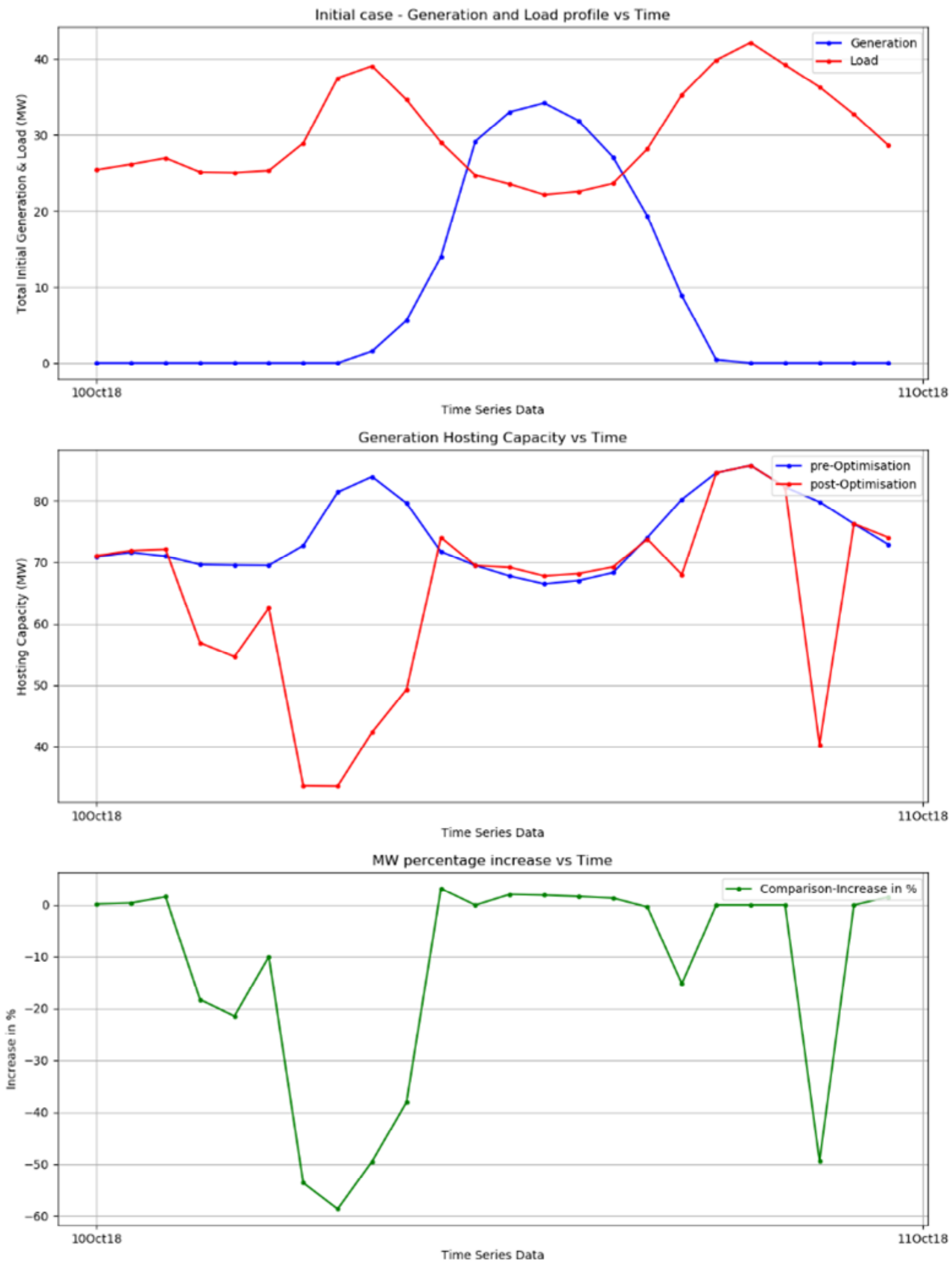


Figure 7-1 - Reducing thermal loading optimisation results

7.4.2. Optimising to Reduce Bus Voltages in the Network

Figure 7-2 shows time series results for Tiverton 33 kV BSP network with a contingency of the 132/32 kV Transformer G2 and optimising to reduce the network voltages. The results show that by optimising to reduce network voltages the reactive dispatch was able to provide at least the same an increase in the post optimisation capacity for 8 out of the 24 time series cases studies (33.3 %).

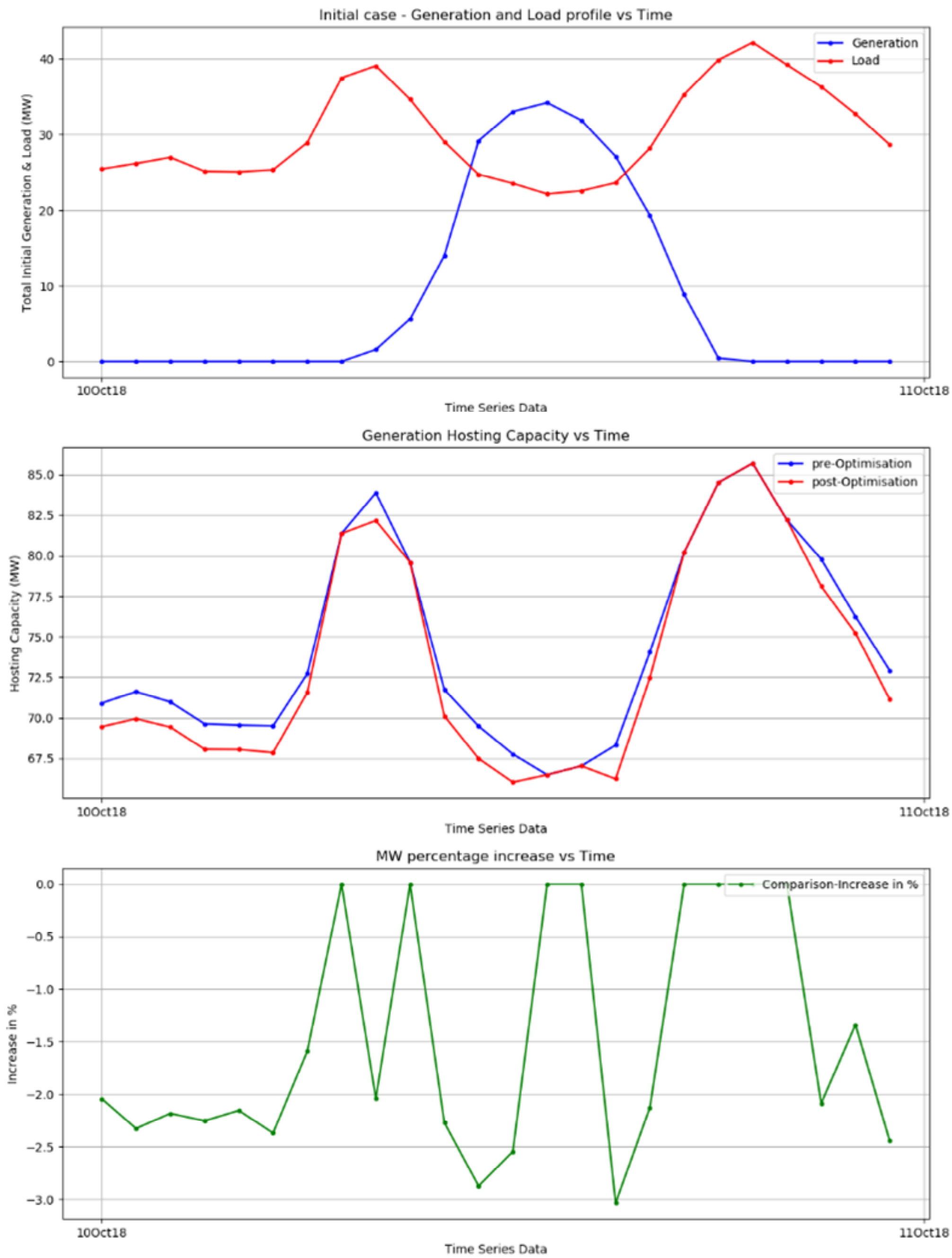


Figure 7-2 - Reducing network voltages loading optimisation results

7.4.3. Optimised based on Calculated Weighting Factor per Feeder Group

Figure 7-3 shows time series results for Tiverton 33 kV BSP network with a contingency of the 132/32 kV Transformer G2 and optimising based on the calculated feeder group weighting factors. The results show that by optimising based on feeder group weighting factors, the reactive dispatch was able to achieve at least the same or an increase in the post optimisation capacity for 9 out of the 24 time series cases studies (37.5%).

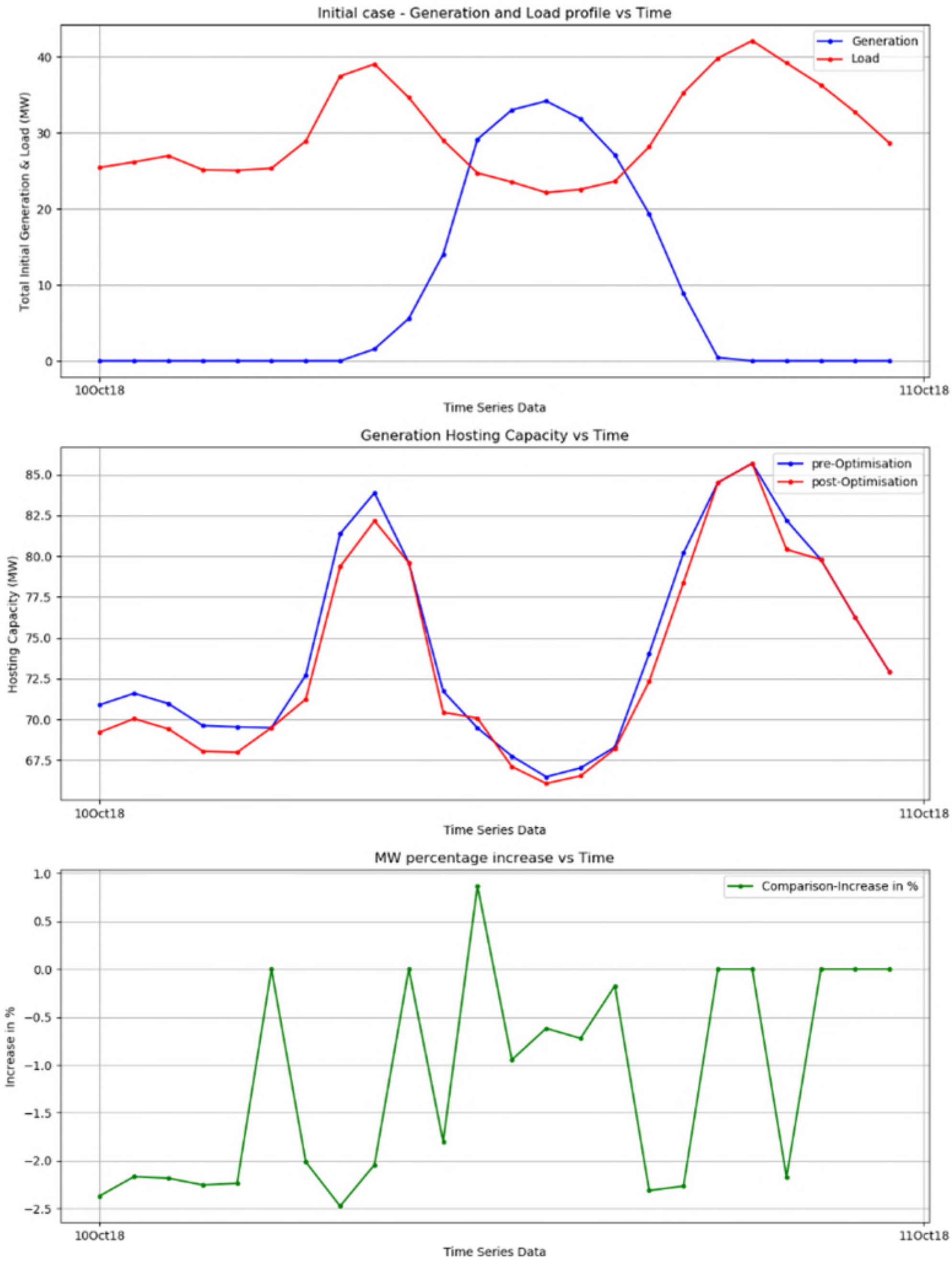


Figure 7-3 – Weighting factor optimisation results

7.5. Summary of Time Series Capacity Benefit Results

This section presents a summary of the generation and load hosting time series results for Tiverton 33 kV BSP network, Barnstaple 33 kV BSP, Pyworthy and North Tawton 33 kV BSP and Tiverton Moorhayes 11 kV Primary. The detailed timeseries hosting results for each network are included in Appendix D and Appendix E. The time series generation hosting results presented here applied the feeder group weighting factor optimisation. The time series load hosting results presented here applied the reduced thermal loadings optimisation. The results present the intact system, best and worst contingency configurations, detailed in Section 7.3.1.

7.5.1. Tiverton 33 kV BSP – Generation

Table 7-4 shows a summary of the time series generation hosting capacity results in the Tiverton 33 kV BSP network. The Virtual Statcom using feeder group weighting optimisation has provided benefit in some but not all time series cases.

Table 7-4: Generation hosting capacity time series summary in Tiverton 33 kV BSP

Network: Tiverton 33 kV BSP Load/Generation Scenario: Time Series load and generation								
Contingency Configuration	Capacity benefit in every time series case				% of Cases with benefit of 0 MW and above			
	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
Intact system	×	×	×	×	33%	52%	20%	39%
Best contingency	×	×	×	×	38%	59%	38%	30%
Worst contingency	×	×	×	×	25%	36%	27%	38%

Figure 7-4 and Figure 7-5 show the average MW increase and percentage increase respectively for Tiverton 33 kV BSP generation hosting capacity with optimised reactive power dispatch for the time series studies. It can be seen that on average the capacity increase is negative except in the winter intact system and spring best continency configuration studies which show an average capacity benefit of just above 0%.

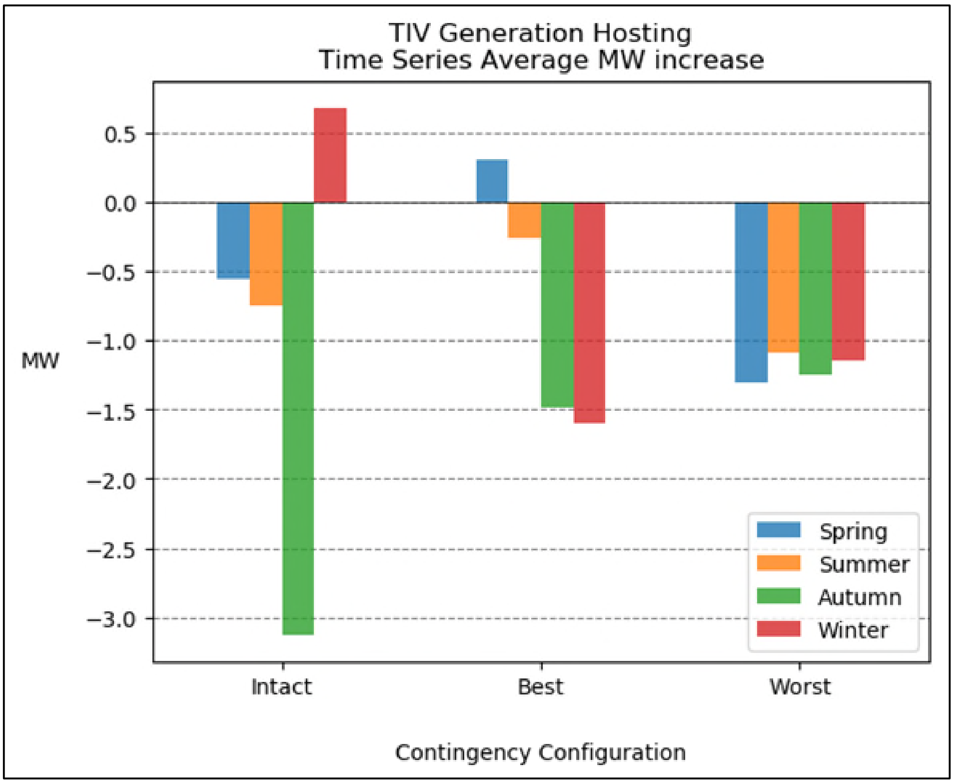


Figure 7-4 - Tiverton 33kV BSP time series average generation hosting increase (MW)

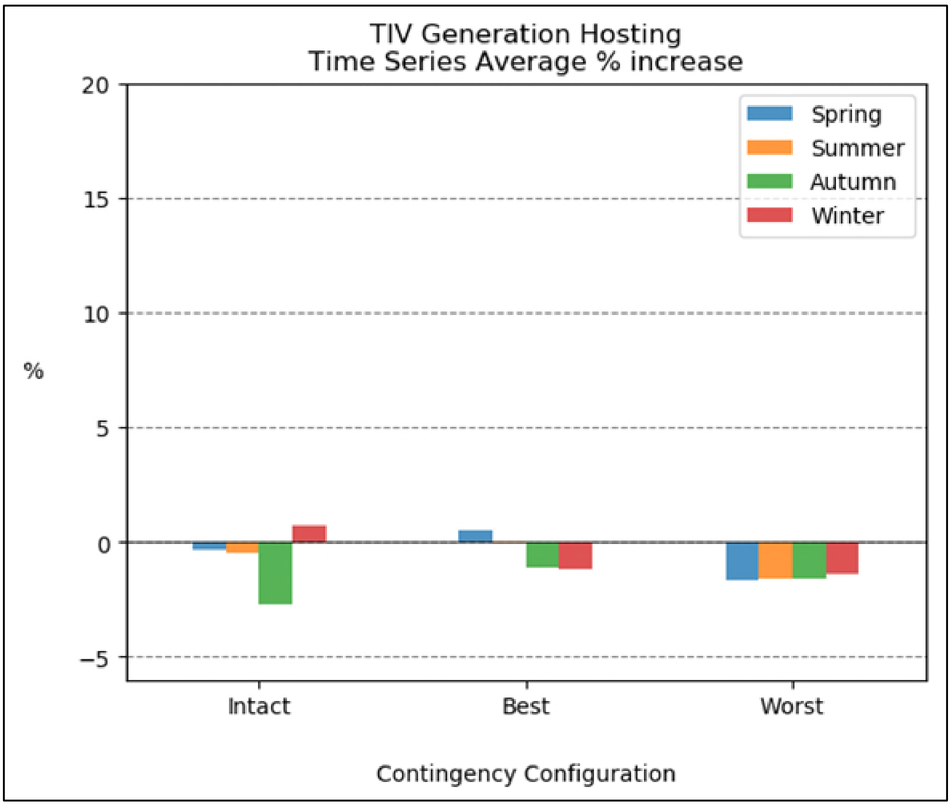


Figure 7-5 - Tiverton 33kV BSP time series average generation hosting increase (%)

7.5.2. Tiverton 33 kV BSP – Load

Table 7-5 shows a summary of the time series load hosting capacity results in the Tiverton 33 kV BSP network. The Virtual Statcom using optimisation to reduce thermal loading has provided benefit in all timeseries cases.

Table 7-5: Load hosting capacity time series summary in Tiverton 33 kV BSP

Network: Tiverton 33 kV BSP Load/Generation Scenario: Time Series load and generation								
Contingency Configuration	Capacity benefit in every time series case				% of Cases with benefit of 0 MW and above			
	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
Intact system	✓	✓	✓	✓	100%	100%	100%	100%
Best contingency	✓	✓	✓	✓	100%	100%	100%	100%
Worst contingency	✓	✓	✓	✓	100%	100%	100%	100%

Figure 7-6 and Figure 7-7 show the average MW increase and percentage increase respectively for Tiverton 33 kV BSP load hosting capacity with optimised reactive power dispatch for the time series studies. It can be seen that on average the capacity increase is positive for all timeseries studies providing an average load hosting capacity benefit of greater than 6% in all seasons and contingency configurations.

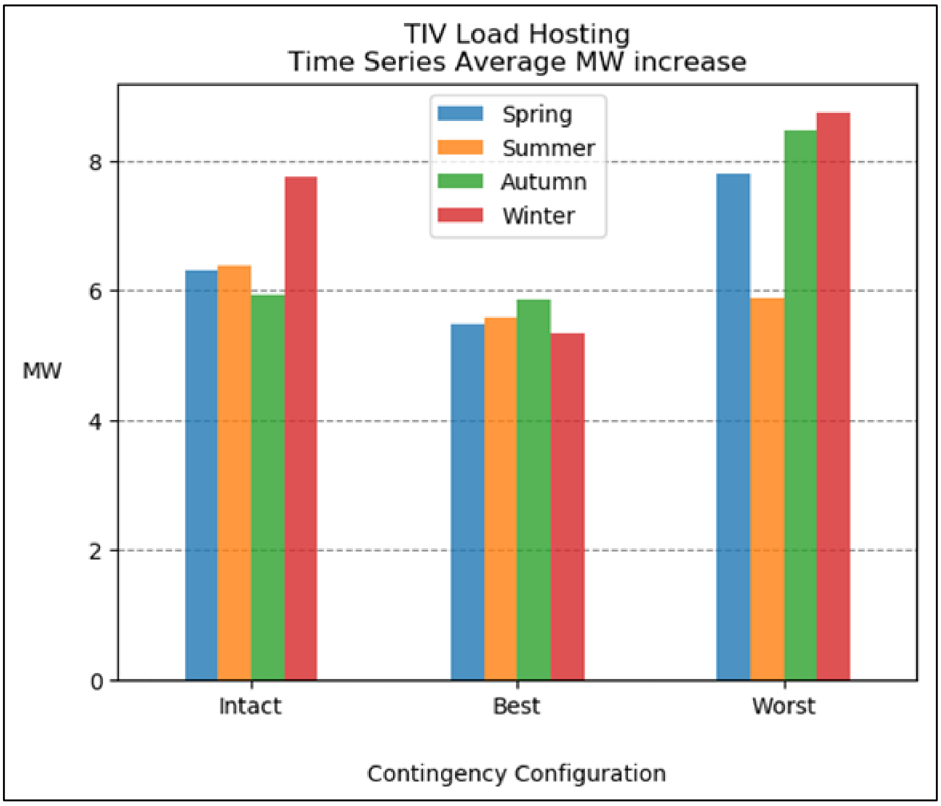


Figure 7-6 - Tiverton 33kV BSP time series average load hosting increase (MW)

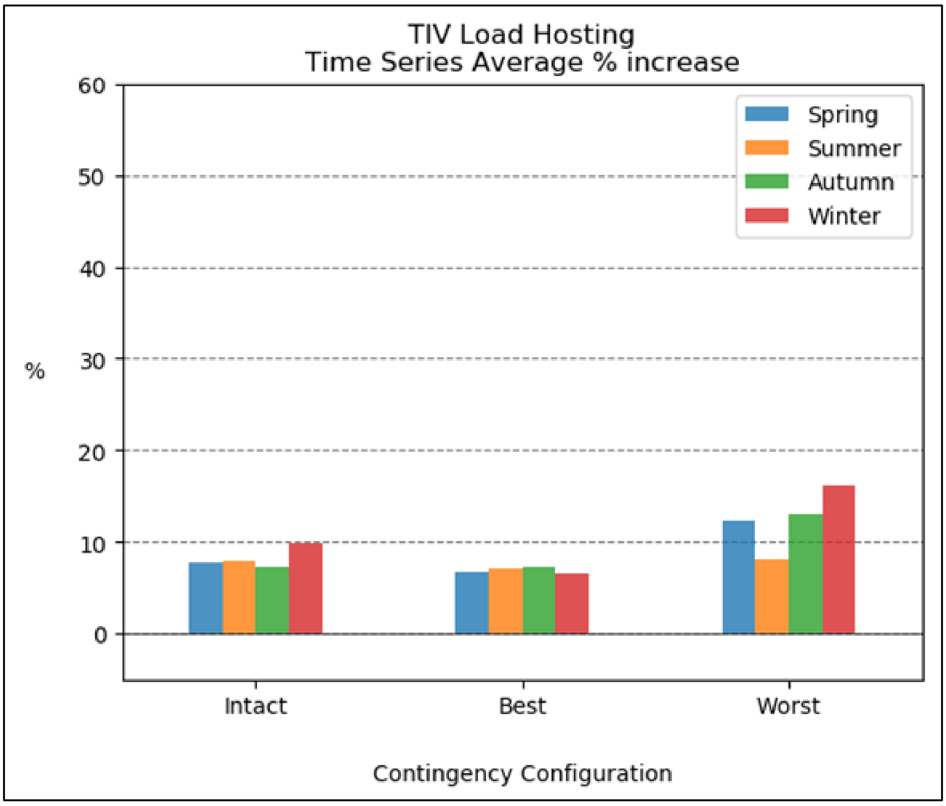


Figure 7-7 - Tiverton 33kV BSP time series average load hosting increase (%)

7.5.3. Barnstaple 33 kV BSP – Generation

Table 7-6 shows a summary of the time series generation hosting capacity results in the Barnstaple 33 kV BSP network. The Virtual Statcom using feeder group weighting optimisation has provided benefit in some but not all time series cases.

Table 7-6: Generation hosting capacity time series summary in Barnstable 33 kV BSP

Network: Barnstaple 33 kV BSP Load/Generation Scenario: Time Series load and generation								
Contingency Configuration	Capacity benefit in every time series case				% of Cases with benefit of 0 MW and above			
	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
Intact system	×	×	×	×	16%	16%	2%	2%
Best contingency	×	×	×	×	5%	2%	9%	7%
Worst contingency	×	×	×	×	23%	29%	20%	21%

Figure 7-8 and Figure 7-9 show the average MW increase and percentage increase respectively for Barnstaple 33 kV BSP generation hosting capacity with optimised reactive power dispatch for the time series studies. It can be seen that on average the capacity increase is negative for all time series studies.

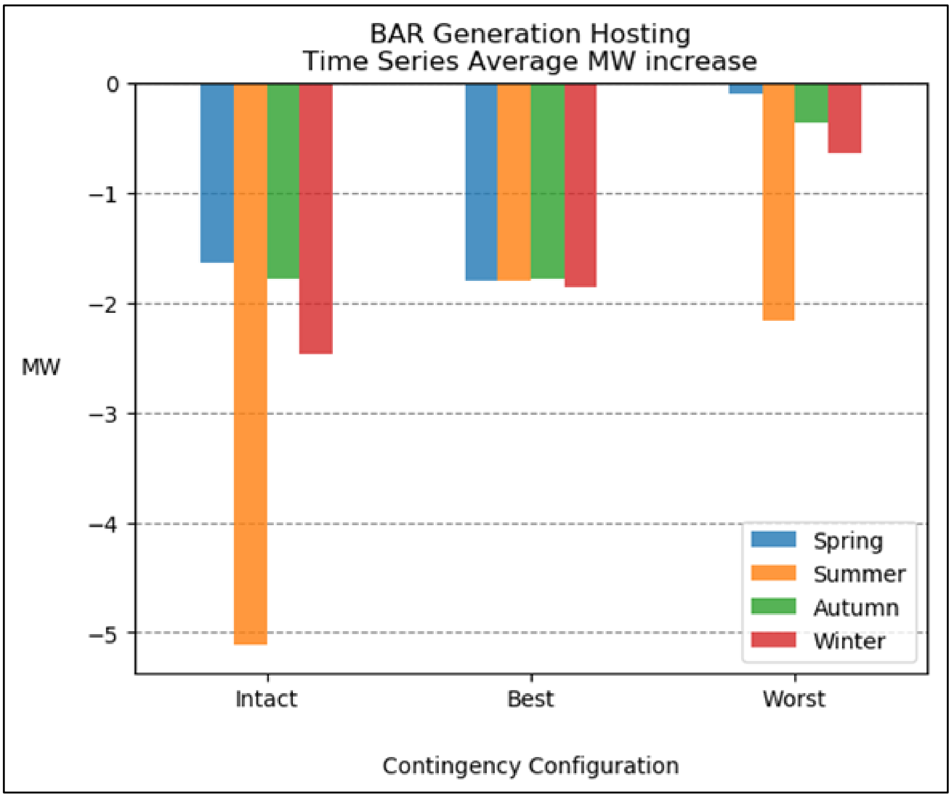


Figure 7-8 - Barnstaple 33kV BSP time series average generation hosting increase (MW)

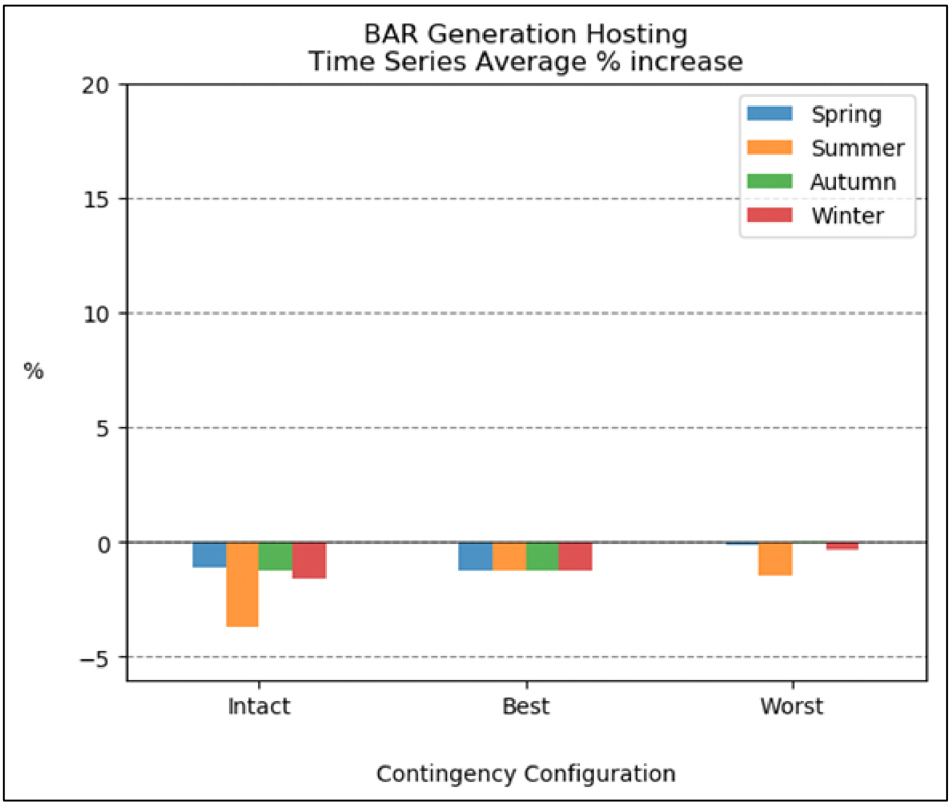


Figure 7-9 - Barnstaple 33kV BSP time series average generation hosting increase (%)

7.5.4. Barnstaple 33 kV BSP – Load

Table 7-7 shows a summary of the time series load hosting capacity results in the Barnstaple 33 kV BSP network. The Virtual Statcom using optimisation to reduce thermal loadings has provided benefit in all timeseries cases.

Table 7-7: Load hosting capacity time series summary in Barnstable 33 kV BSP

Network: Barnstaple 33 kV BSP Load/Generation Scenario: Time Series load and generation								
Contingency Configuration	Capacity benefit in every time series case				% of Cases with benefit of 0 MW and above			
	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
Intact system	✓	✓	✓	✓	100%	100%	100%	100%
Best contingency	✓	✓	✓	✓	100%	100%	100%	100%
Worst contingency	✓	✓	✓	✓	100%	100%	100%	100%

Figure 7-10 and Figure 7-11 show the average MW increase and percentage increase respectively for Barnstaple 33 kV BSP load hosting capacity with optimised reactive power dispatch for the time series studies. It can be seen that on average the capacity increase is positive for all timeseries studies providing significant average load hosting capacity benefit in all seasons and contingency configurations.

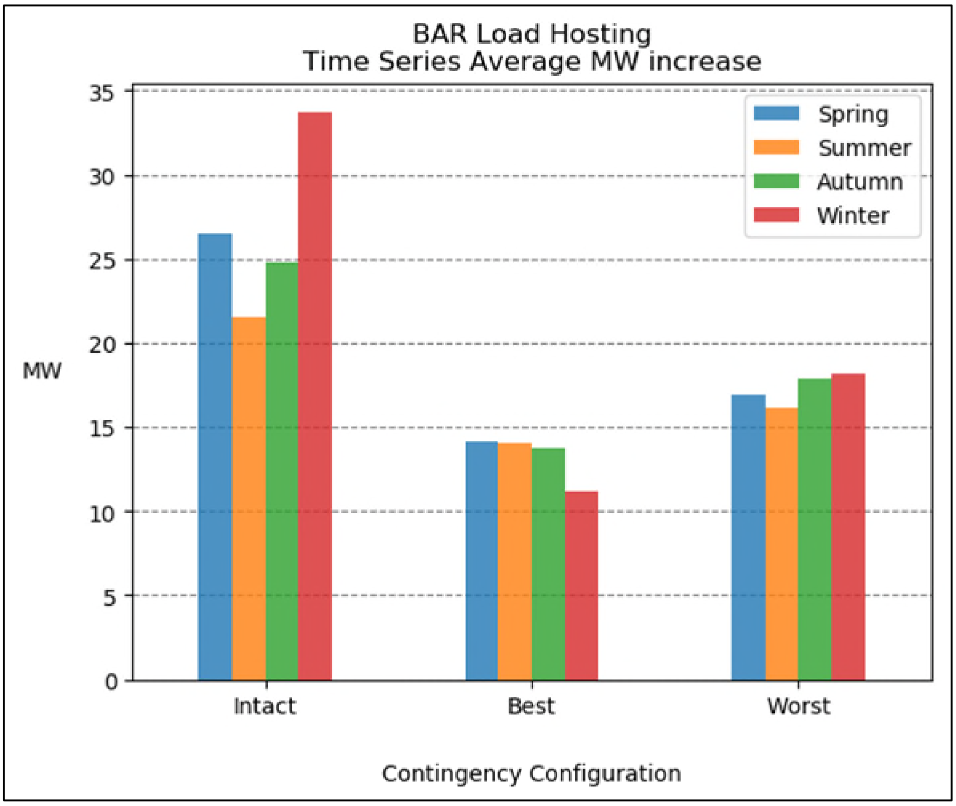


Figure 7-10 - Barnstaple 33kV BSP time series average load hosting increase (MW)

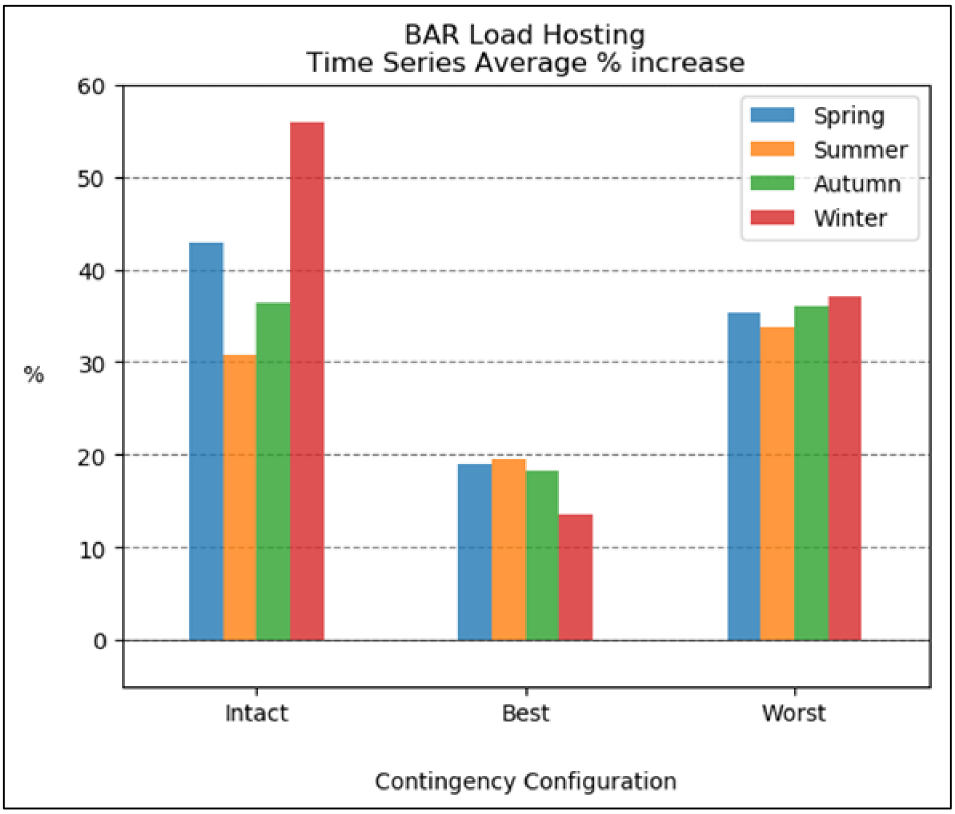


Figure 7-11 - Barnstaple 33kV BSP time series average load hosting increase (%)

7.5.5. Pyworthy and North Tawton 33 kV BSP – Generation

Table 7-8 shows a summary of the time series generation hosting capacity results in the Pyworthy and North Tawton 33 kV BSP network. The Virtual Statcom using feeder group weighting optimisation has provided benefit in some but not all time series cases.

Table 7-8: Generation hosting capacity time series summary in Pyworthy and North Tawton 33 kV BSP

Network: Pyworthy and North Tawton 33 kV BSPs Load/Generation Scenario: Time Series load and generation								
Contingency Configuration	Capacity benefit in every time series case				% of Cases with benefit of 0 MW and above			
	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
Intact system	×	×	×	×	41%	45%	39%	46%
Best contingency	×	×	×	×	50%	41%	46%	46%
Worst contingency	×	×	×	×	54%	73%	63%	61%

Figure 7-12 and Figure 7-13 show the average MW increase and percentage increase respectively for Pyworthy and North Tawton 33 kV BSPs generation hosting capacity with optimised reactive power dispatch for the time series studies. It can be seen that on average the capacity increase is negative for the intact and best contingency configurations. In the worst contingency configuration on average there is a positive benefit in summer, autumn and winter cause by a small number of time series cases having a large generation capacity increase.

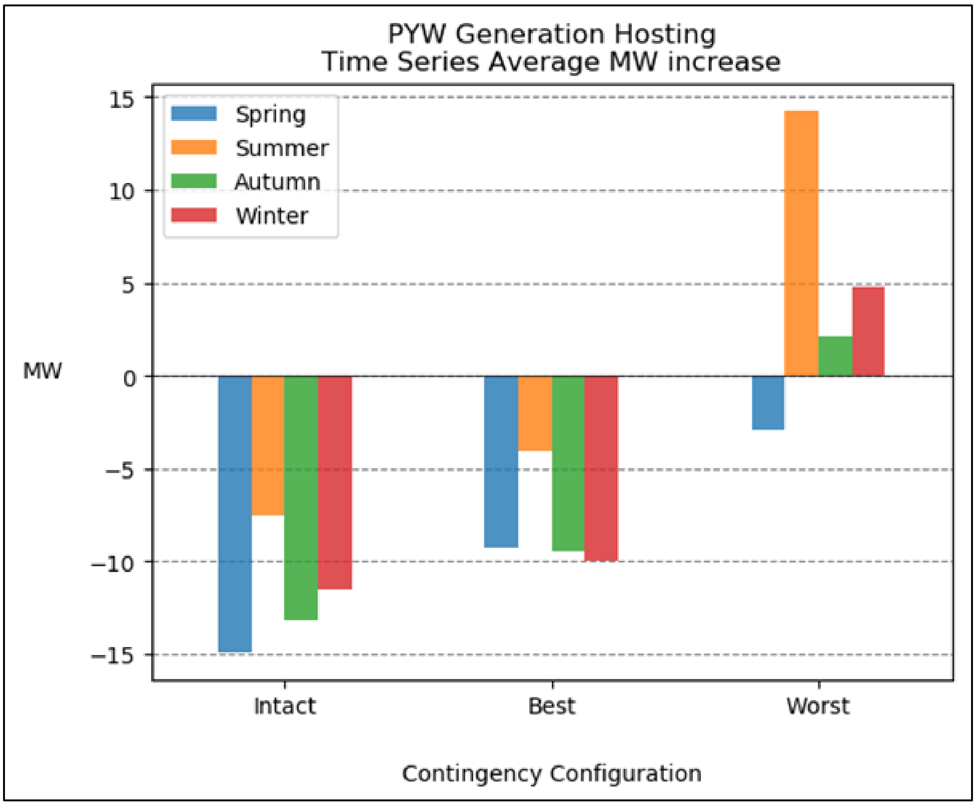


Figure 7-12 - Pyworthy and North Tawton 33kV BSP time series average generation hosting increase (MW)

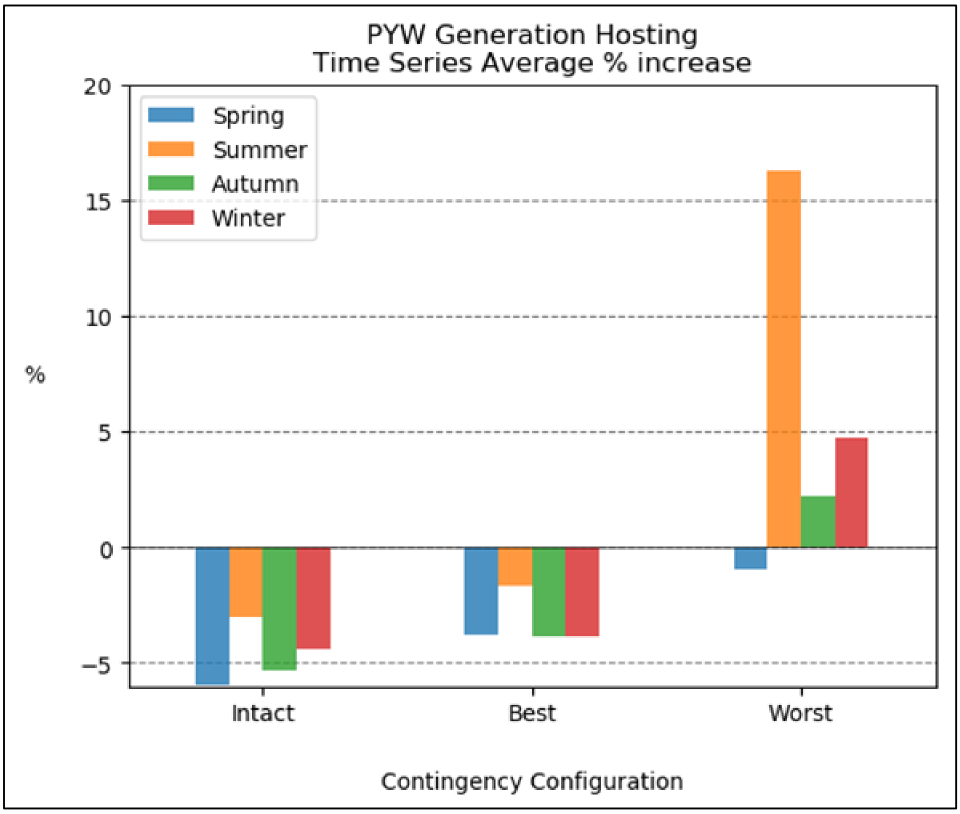


Figure 7-13 - Pyworthy and North Tawton 33kV BSP time series average generation hosting increase (%)

7.5.6. Pyworthy and North Tawton 33 kV BSP – Load

Table 7-9 shows a summary of the time series load hosting capacity results in the Pyworthy and North Tawton 33 kV BSP network. The Virtual Statcom using optimisation to reduce thermal loadings has provided benefit in all timeseries cases, except one. The exception is in a time series case, where the aggregated SCADA data shows loads to be capacitive (exporting Mvar). This is then scaled at a constant power factor resulting in voltage increases across the system rather than the voltage reduction that would be experienced with increasing load.

Table 7-9: Load hosting capacity time series summary in Pyworthy and North Tawton 33 kV BSP

Network: Pyworthy and North Tawton 33 kV BSPs Load/Generation Scenario: Time Series load and generation								
Contingency Configuration	Capacity benefit in every time series case				% of Cases with benefit of 0 MW and above			
	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
Intact system	✓	✓	✓	✓	100%	100%	100%	100%
Best contingency	×	✓	✓	✓	98%	100%	100%	100%
Worst contingency	✓	✓	✓	✓	100%	100%	100%	100%

Figure 7-14 and Figure 7-15 show the average MW increase and percentage increase respectively for Pyworthy and North Tawton 33 kV BSP load hosting capacity with optimised reactive power dispatch for the time series studies. It can be seen that on average the capacity increase is positive for all timeseries studies providing an average load hosting capacity benefit of greater than 5% in all seasons and contingency configurations.

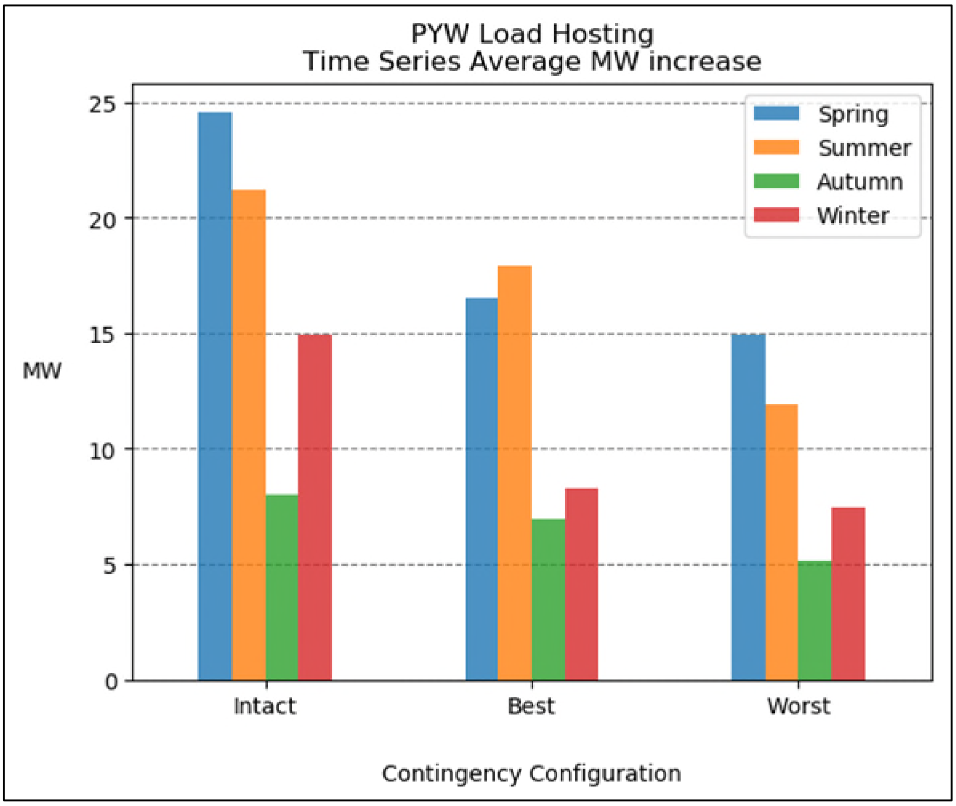


Figure 7-14 - Pyworthy and North Tawton 33kV BSP time series average load hosting increase (MW)

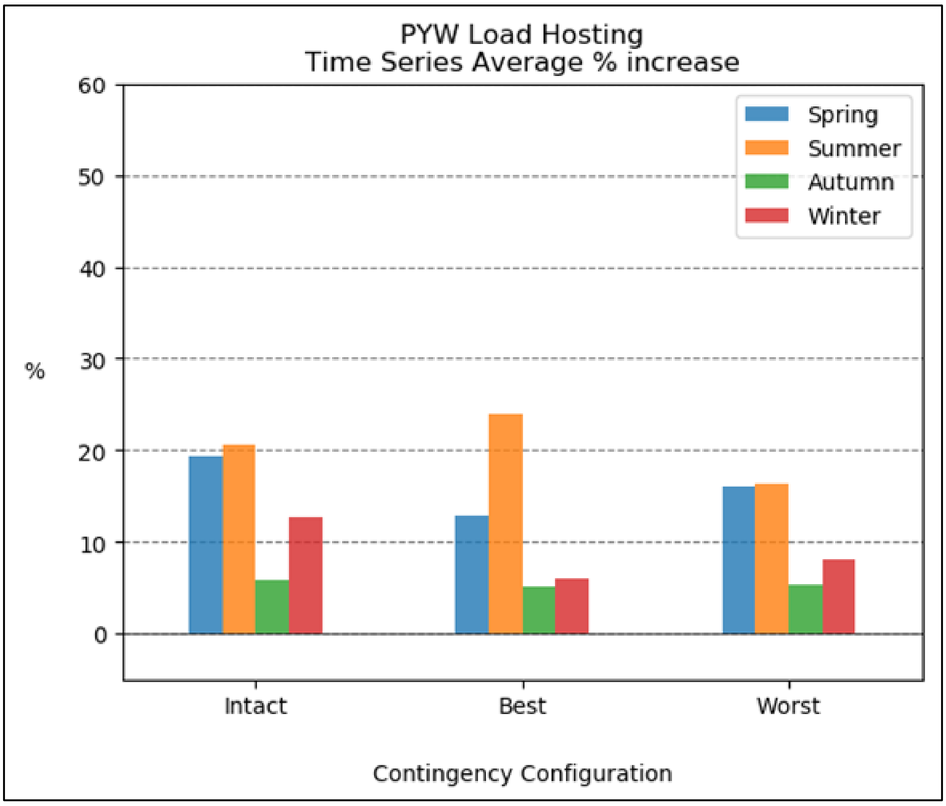


Figure 7-15 - Pyworthy and North Tawton 33kV BSP time series average load hosting increase (%)

7.5.7. Tiverton Moorhayes 11 kV Primary – Generation

Table 7-10 shows a summary of the time series generation hosting capacity results in the Tiverton Moorhayes 11 kV Primary network. The Virtual Statcom using feeder group weighting optimisation has provided benefit in some but not all time series cases.

Table 7-10: Generation hosting capacity time series summary in Tiverton Moorhayes 11 kV Primary

Network: Tiverton Moorhayes 11 kV Primary Load/Generation Scenario: Time Series load and generation								
Contingency Configuration	Capacity benefit in every time series case				% of Cases with benefit of 0 MW and above			
	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
Intact system	×	×	×	×	25%	36%	21%	48%
Best contingency	×	×	×	×	32%	54%	41%	61%
Worst contingency	×	×	×	×	23%	20%	18%	50%

Figure 7-16 and Figure 7-17 show the average MW increase and percentage increase respectively for Tiverton Moorhayes 11 kV Primary generation hosting capacity with optimised reactive power dispatch for the time series studies. It can be seen that on average the capacity increase is negative for all time series studies except the best contingency configuration summer case. The averages are very close to zero due to the small amount of reactive power available from the two generators in the network.

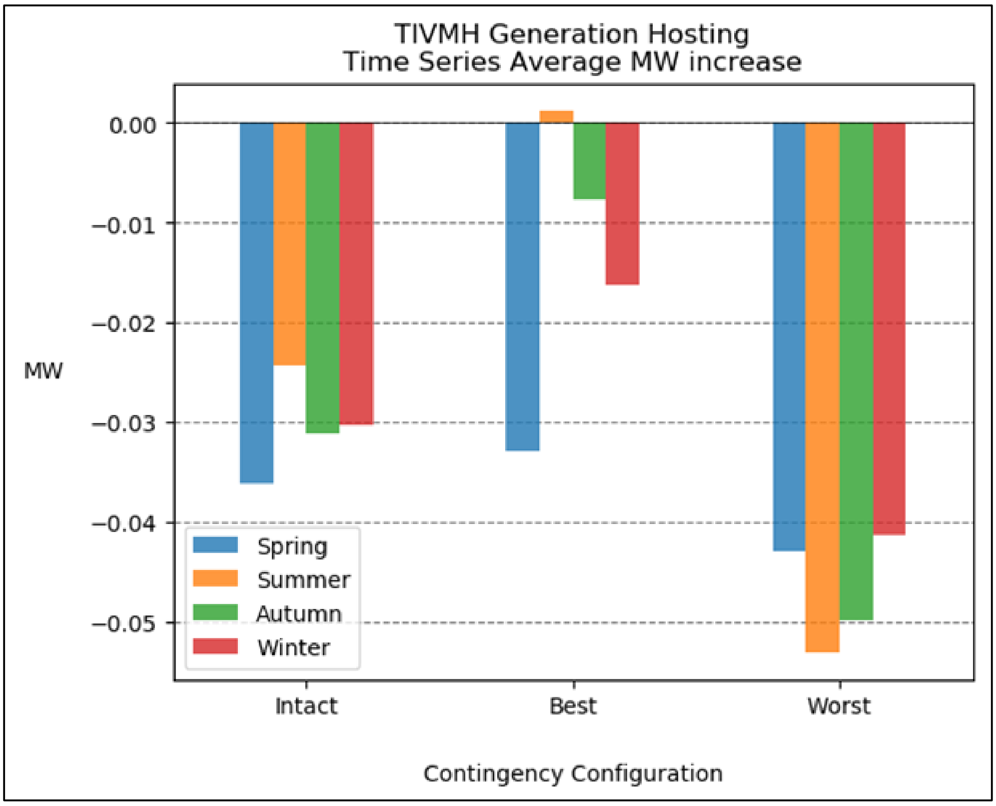


Figure 7-16 - Tiverton Moorhayes 11 kV Primary time series average generation hosting increase (MW)

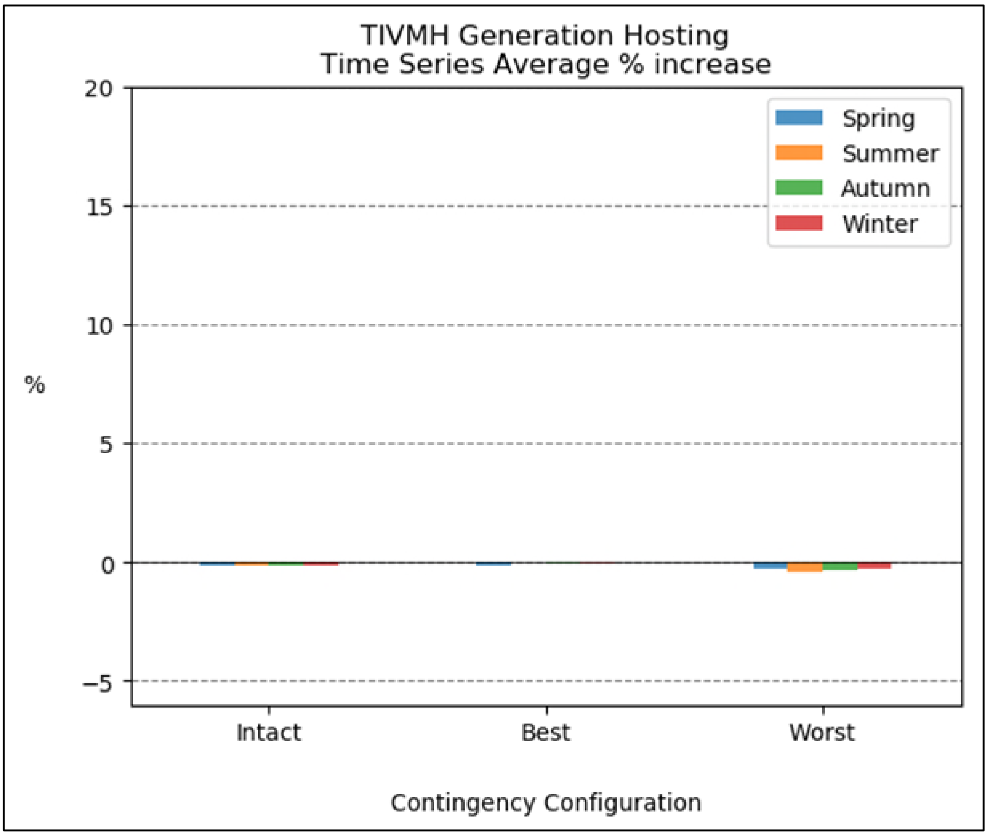


Figure 7-17 - Tiverton Moorhayes 11 kV Primary BSP time series average generation hosting increase (%)

7.5.8. Tiverton Moorhayes 11 kV Primary – Load

Table 7-11 shows a summary of the time series load hosting capacity results in the Tiverton Moorhayes 11 kV Primary network. The Virtual Statcom using optimisation to reduce thermal loadings has provided a small benefit in the majority of timeseries cases however for low parentage of combinations of generation and load failed to provide at least the same load hosting capacity.

Table 7-11: Load hosting capacity time series summary in Tiverton Moorhayes 11 kV Primary

Network: Tiverton Moorhayes 11 kV Primary Load/Generation Scenario: Time Series load and generation								
Contingency Configuration	Capacity benefit in every time series case				% of Cases with benefit of 0 MW and above			
	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
Intact system	×	×	×	×	95%	96%	93%	98%
Best contingency	×	×	×	✓	95%	84%	95%	100%
Worst contingency	×	✓	×	✓	98%	100%	98%	100%

Figure 7-18 and Figure 7-19 show the average MW increase and percentage increase respectively for Tiverton Moorhayes 11 kV Primary load hosting capacity with optimised reactive power dispatch for the time series studies. It can be seen that on average the capacity increase is positive for the timeseries studies except the best contingency configuration in spring and summer cases, the best case contingency results in only one generator being available to optimise.

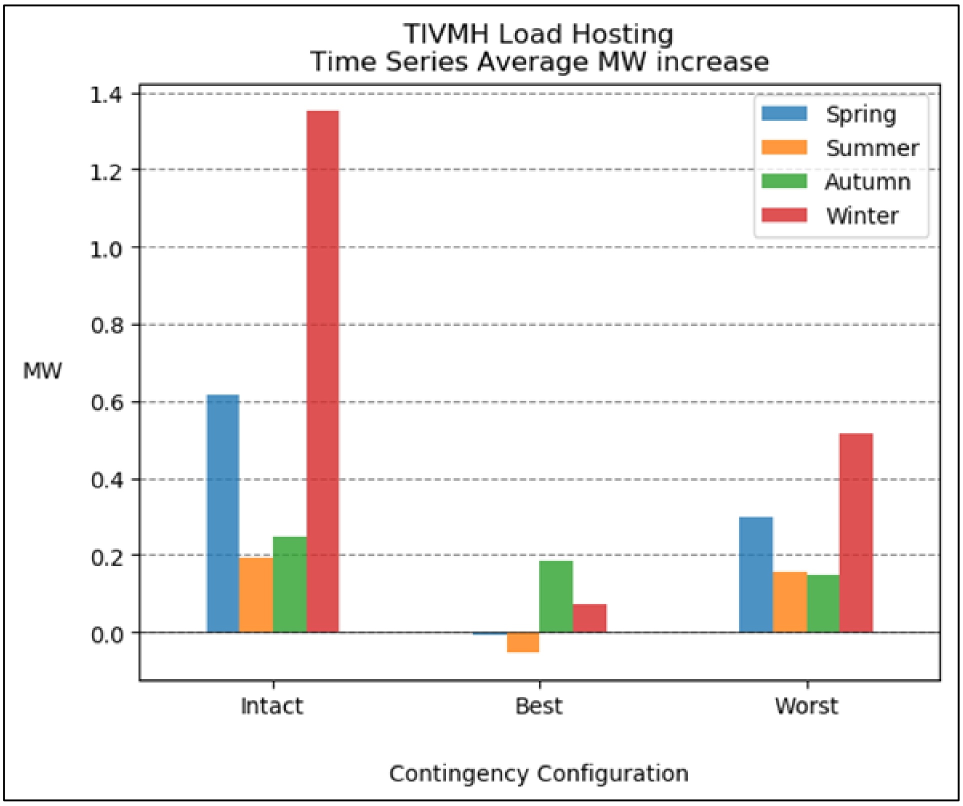


Figure 7-18 - Tiverton Moorhayes 11 kV Primary time series average load hosting increase (MW)

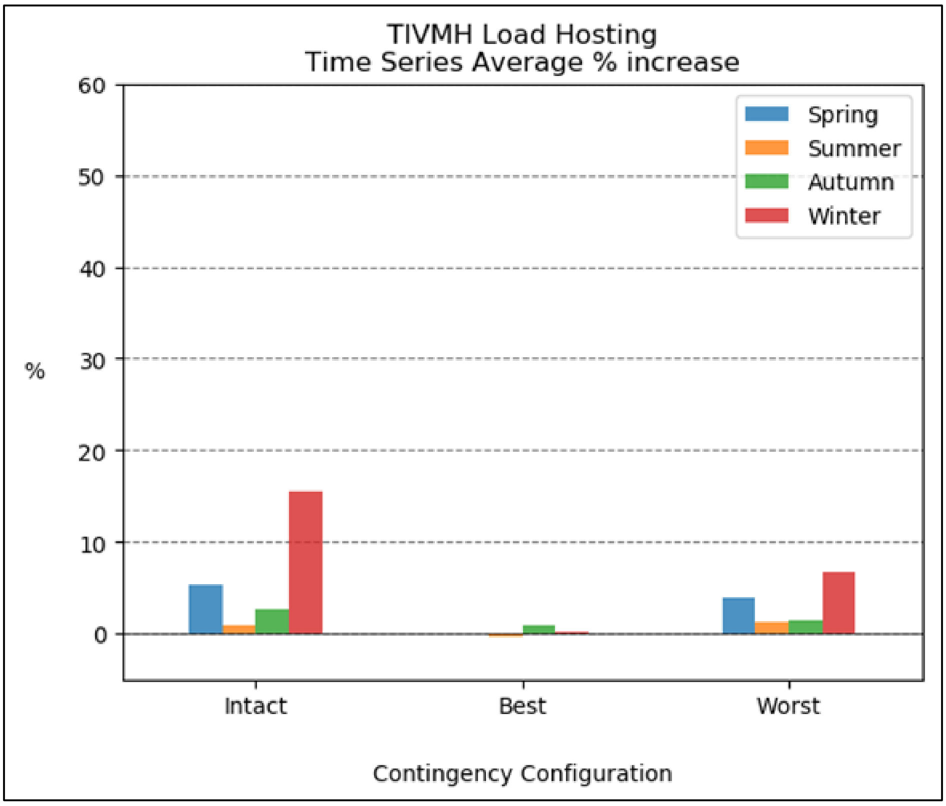


Figure 7-19 - Tiverton Moorhayes 11 kV Primary BSP time series average load hosting increase (%)

7.6. Analysis of Time Series Generation Hosting Results

The time series generation hosting capacity results that compare objective functions over a single day presented in this section show that no one method of optimisation produces a benefit under all system condition and configurations, these results are in line with the findings from the non-time series results.

The seasonal weeks results for the weighting factor objective function presented in this section show that there are cases where the automatic feeder group weighting factor provided benefit in some configurations but in others the optimised reactive power dispatch resulted in a reduced hosting capacity. This shows that the minimisation of the weighting factor objective function does not guarantee the same or increased hosting capacity across all network configuration and generation and load scenarios.

The method that has been applied for the feeder group weighting factor aims to identify the constraint that will limit the hosting capacity in each feeder group. This is achieved through an assumption that voltages and circuit loading will increase linearly from the starting point until the first constraint is reached. However, further analysis of the results has shown that the generation hosting capacity algorithm is able to overcome the first constraint and therefore a different constraint becomes the hosting capacity limiting point. Additionally, in networks with significant hosting capacity available, the voltages do not follow a linear increase and it is therefore necessary to continuously re-assess the network constraints as the network operation changes. Further discussion and analysis around the weighting factor optimisation method and its limitations is provided in Section 8.

7.7. Analysis of Time Series Load Hosting Results

The time series load hosting capacity results presented in this section show that by optimising reactive power set points to reducing thermal loadings in a network produces a benefit under almost all system condition and configurations. These results are in line with the findings from the non-time series results.

8. Feeder Group Approach Analysis

The aim of the feeder group approach was to develop a method that could find a balance between the conflicting optimisation options of; reducing system voltages or reducing thermal loading at a feeder group level. The generation hosting results presented in this report show that after optimising reactive power set points based on calculated feeder group weightings, the generation hosting capacity can be less than the hosting capacity achieved with the initial PSS/E case's reactive power dispatch. This section presents analysis undertaken to understand this and determine the limitations of the feeder group weighting based optimisation.

8.1. Feeder Group Weighting Calculation Analysis

The feeder group weighting calculation presented in Section 5.1, developed on the minimum load and maximum generation scenario, is based on a small increase in generation and then estimating whether a feeder group will become voltage or thermally constrained first when increasing generation. This approach was applied with the assumption that the optimisation algorithm needs to be able to establish reactive power set-points without knowledge of the final generation hosting capacity and therefore assumes that the system voltages and thermal loadings follow a linear trajectory for increases in generation.

Analysis of time series results with low levels or no network generation identified that the feeder group weighting calculation cannot always determine how each feeder group will be constrained in a future generation scenario. The main reason for this is the assumption that the bus voltage and thermal loading trajectories continue in a linear fashion does not hold true when there is still significant headroom for generation increase. This assumption does not hold true due to the non-linear nature of bus voltages when increasing network generation.

Additionally, the weighting factor calculation makes no allowance for whether a reduced hosting capacity in one feeder group may allow for a greater increase in another feeder group. In this situation the overall network capacity as a result of the sum of all of the feeder groups may have increased.

8.1.1. Non-linear Characteristic of Network Bus Voltages

Analysis of the generation hosting results presented in this report identified that the further the network case is away (in MW) from the generation hosting capacity, the less likely the feeder group weighting calculation can accurately determine when (in MW) a feeder group is going to become thermally or voltage constrained when increasing generation. This is due to the non-linear characteristics of network voltages, when increasing generation which are not seen for smaller generation increases. In the worst case the non-linear nature of, in particular bus voltages, can cause the weighting factor calculation to determine a feeder group will reach a voltage constraint first rather than a thermal constraint. The values of weighting factors can differ slightly depending on the location of the generation scaled in the network, but this is not significant enough to cause the calculation to determine the constraint type incorrectly.

Figure 8-1 shows Tiverton 33 kV BSP bus voltages and feeder loadings when increasing generation in each feeder group, in 1 MW increments, with a contingency of Tiverton 132/33 kV transformer T2 for the minimum load maximum generation scenario. In Figure 8-1, it can be seen that the 33 kV bus voltages are approximately linear by the black dotted line in each of the 33 kV bus plots. Figure 8-2 provides comparison for the same contingency for the maximum load, 10% generation scenario. It shows that the 33 kV bus voltages are non-linear compared to the black dotted line. The non-linear bus voltages cause the feeder group weighting factor calculation to determine that feeder groups 0 and 2 are constrained by the upper voltage limit of 1.06 p.u., however the bus voltages in these feeder groups reach a maximum bus voltage and then decrease, suggesting the limiting factor will be the thermal loading.

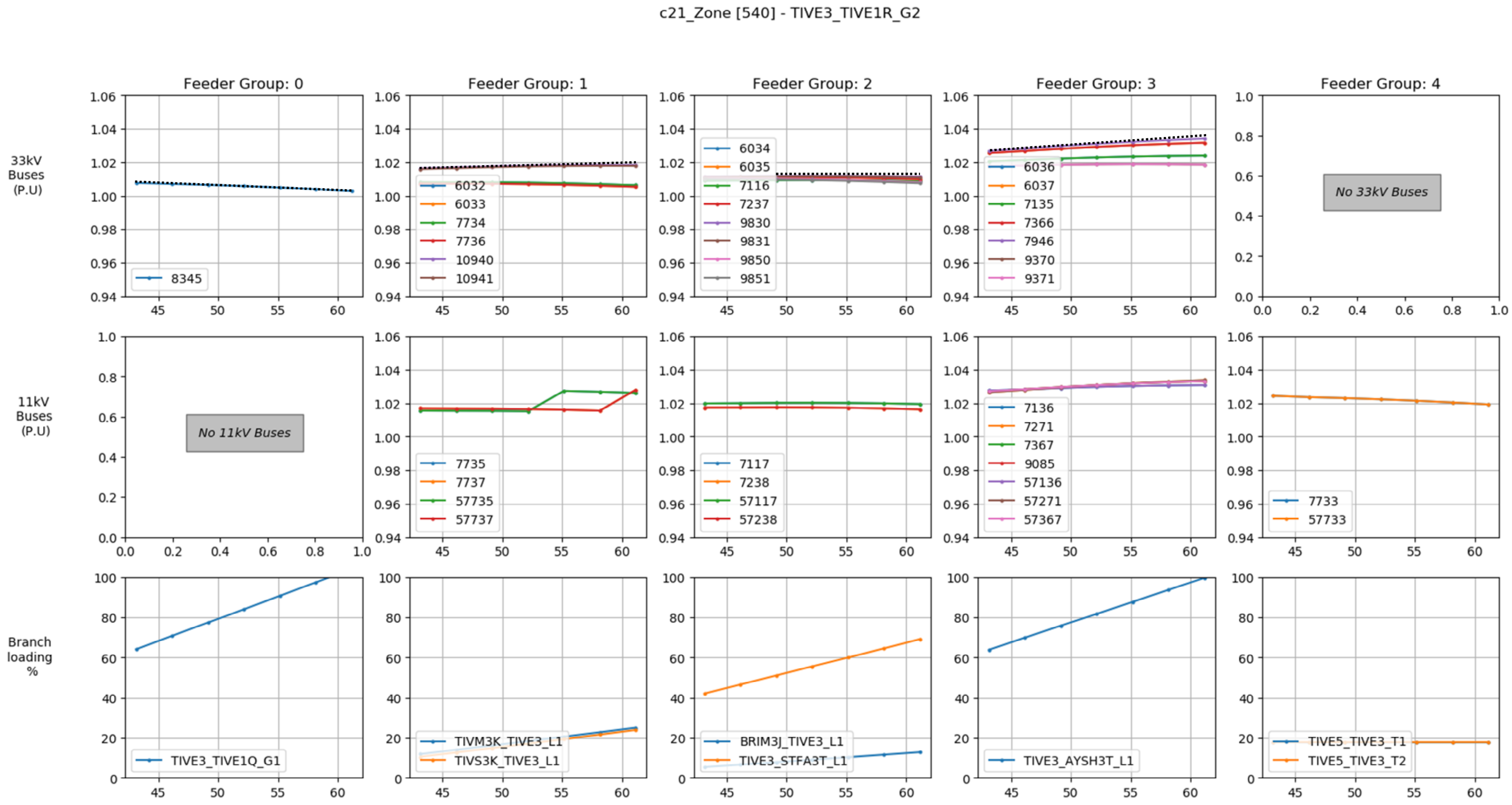


Figure 8-1 - Tiverton 33 kV BSP Feeder groups bus voltage and feeder loadings for increasing generation (minimum load maximum generation scenario)

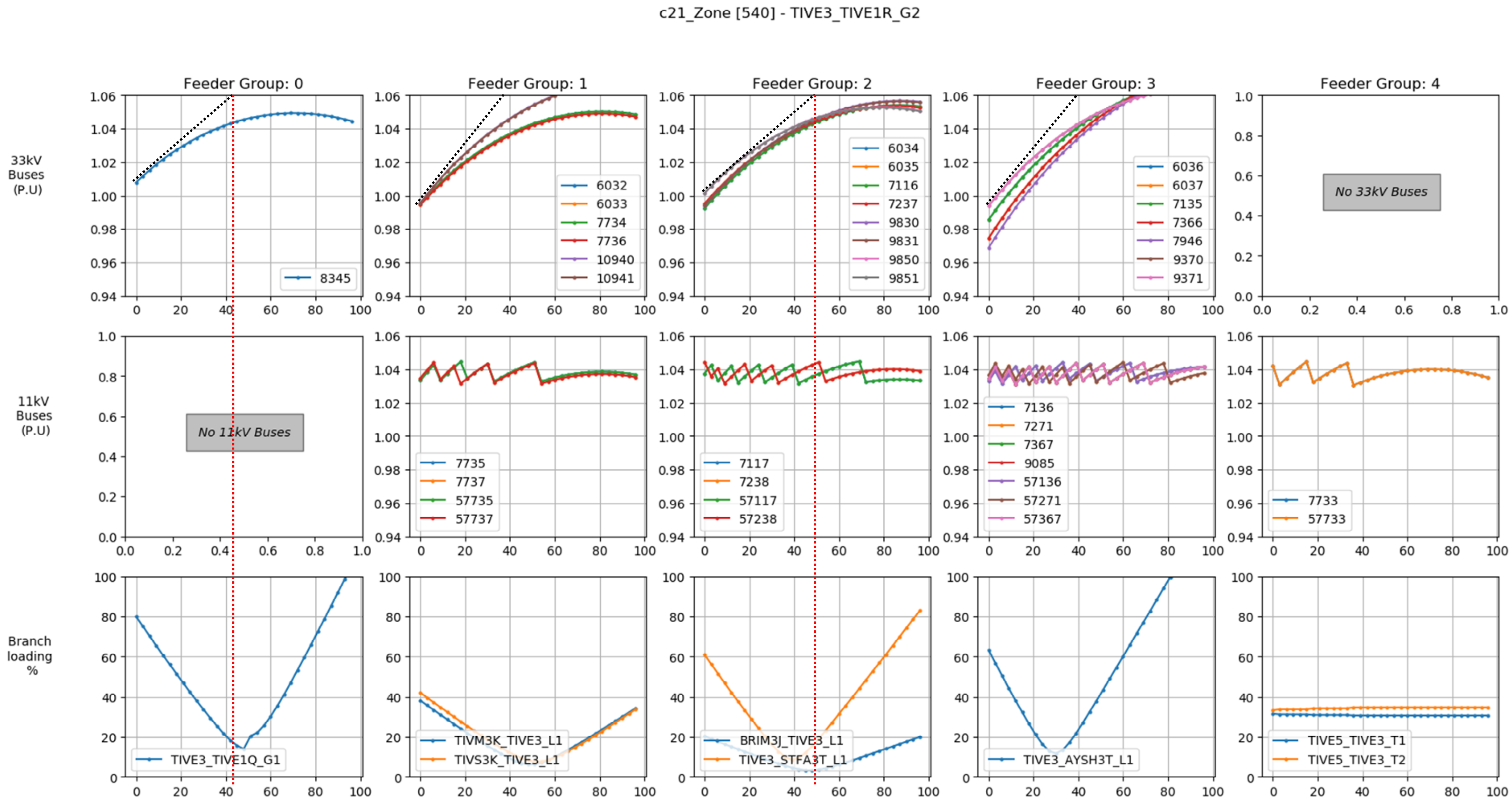


Figure 8-2 - Tiverton 33 kV BSP Feeder groups bus voltage and feeder loadings for increasing generation (maximum load minimum generation scenario)

8.1.2. Whole System Hosting Capacity

The weighting factor calculation aims to increase the headroom available for generation hosting in each feeder group. This is achieved by either reducing thermal loading or system voltages in each feeder group to allow a greater increase before the first limiting constraint is reached. This approach aims to increase the hosting capacity in all feeder groups within a network even though there may be conflicting improvements, reducing losses in one feeder group leads to increasing voltages in another feeder group. A result of this approach is that in many cases only a very small benefit can be achieved in one feeder group without negatively impacting another feeder group.

The limitation of this approach is it does not consider the potential to optimise the hosting capacity for the complete network. In some situations, it may be beneficial to allow a reduction in the hosting capacity in one feeder group since a greater hosting capacity is possible in another feeder group. The result could then be a greater increase in the whole system hosting capacity. However, to determine this the feeder group weighting calculation would not only need to estimate when each feeder group would reach its limit but also the interaction each feeder group has on each other which would not be achievable without significant increases to the computational time.

8.2. Optimisation using the Feeder Group Weighting Objective Function

The generation hosting results presented in this report demonstrates that the reactive power dispatch of existing generators affects a network's generation hosting capacity. However, the results also show that a generation hosting capacity benefit is not guaranteed when optimising a network based on calculated feeder group weightings for all network configurations. Optimisation to improve generation headroom to increase generation hosting is complex and must achieve a thermal-voltage balance between feeder groups.

Section 8.1 has shown that the calculated feeder group weighting factors could account for the objective function not providing a benefit in all scenarios due to assumptions around the linear operation of the power system. Modern electricity distribution networks are complex in configuration and operation and assumptions cannot be made on the linearity of operating conditions. Therefore, since it is challenging to establish rules for network constraints under the full range of operating conditions, an optimisation system needs to be based on the actual or final system conditions.

If the hosting capacity or constraint point for a specific network dispatch scenario is known, then the reactive power set-points can be optimised to resolve the specific constraint and therefore increase hosting capacity. To further investigate this, the following two approaches that have been identified as having the potential to determine if generation hosting capacity benefits in all network configurations is achievable:

1) Using the hosting capacity algorithm to determine feeder group constraints.
2) Direct optimisation of generation hosting capacity.

These approaches are discussed in the following sub sections.

8.2.1. Hosting Capacity Algorithm to Determine Feeder Group Constraints

Section 8.1 has shown the importance of splitting the network into feeder groups is critical in establishing limitations to hosting capacity. The analysis has supported that each feeder group can vary in nature and the limiting constraints. The results have also shown that estimating the limiting constraint and therefore weighting factor for a feeder group may not be the same as the last constraint the limits hosting capacity.

In planning timescales it would be possible to run the hosting capacity algorithm first to identify the final constraint in each feeder group and then subsequently optimise the reactive power to resolve those specific constraints. However, detailed analysis would need to be taken into consideration to determine the specific location that new generation is being connected as this could significantly impact on the constraints.

A real-time system would also benefit from looking at the system, generation/load and contingencies at this level of detail. The optimisation algorithm would be able to identify the constraints on a feeder group level and ensure those are resolved whilst improving the operating position of the rest of the system.

8.2.2. Direct Optimisation of Generation Hosting Capacity:

To investigate the potential for the optimisation algorithm in both planning and real-time scenarios the objective function does not directly optimise the generation hosting capacity of a network. Instead it aims to balance voltage and thermal conflicts to increase the available headroom for generation. This approach was taken to the reduce computational burden of the optimisation process [1].

A direct optimisation approach would use the generation hosting capacity of a network as the objective function, then attempt to maximise this by using different reactive power dispatches. This approach was considered in WP1 when developing objective functions but not favoured due to the heavy computational burden and its inability to easily incorporate contingency configurations for the traditional planning algorithm [1].

A direct approach for individual contingency configurations is likely to be the most accurate method to determine if generation hosting capacity benefit can be achieved through changing the reactive power dispatch of existing generators. However, the downside of this approach is that it would place a significant increase in the computation time as multiple hosting algorithm would need to be run as part of the optimisation algorithm. It would therefore only be appropriate for use in network planning timescales where limited generation and load dispatch scenarios are considered. This approach could provide results such as:

- Accurately determine the generation hosting capacity benefit from controlling existing generators reactive power.
- Determine the maximum output for a new connection if existing generators have controllable reactive power.

To improve the computational time of this approach, particle swarm optimisation has the potential to be applied to determine a network's generation hosting capacity. This approach to hosting capacity was touched on in the WP1 report [1] and the following provides a high-level summary.

1. In a network, identify n candidate buses for new distributed generation.
2. Set an objective function to:

$$Maximise \sum_{g=1}^{n} Pg$$

Where $(P_1, P_2, \ldots\ P_n,)$ are the control variables i.e. the real power output of each generator.

Subject to (constraints):

- Bus voltage limits
- Branch flow thermal limits
- Voltage step change limits

8.2.3. Real Time Optimisation of Reactive Power

When operating networks in real time, there is no need to optimise reactive power set points for a future generation scenario but rather optimise the network based on the current system conditions, constraints and likely network events. The work completed in this project has provided valuable learning on the requirement to continuously re-asses the network constraints in order to be able to truly optimise. As the distribution networks become more complex there is a clear need for DSOs to have a Network Management System that is able to run a state estimation and load flow analysis with the right optimisation objectives and a mixture of technologies in order to truly optimise the network operation and capacity.

In a real time system, the priority of the Virtual Statcom could be to resolve or reduce any constraints and if no constrains are present the Virtual Statcom could focus on reducing thermal loadings or system voltages. The reducing thermal loading and reducing voltage non-direct objective functions developed as part of this project could be applied here.

9. Virtual Statcom Project WP3 Conclusions

This report sets out the results and findings for Work Package 4 of the Virtual Statcom project which has developed algorithms to determine the available generation and load hosting capacity. The Virtual Statcom then considers the optimisation of reactive dispatch for existing generators to investigate increasing this hosting capacity and has been investigated on three of the WPD 33 kV BSP networks and one 11 kV Primary network:

- Barnstable 33 kV BSP
- Pyworthy and North Tawton 33 kV BSP
- Tiverton 33 kV BSP
- Tiverton Moorhayes 11 kV Primary

The algorithms developed in Work Package 2 of the Virtual Statcom project have been updated to carry out the capacity and optimisation considering each feeder group within a network zone. This report has presented results for:

- The extremes of the operating positions on WPD networks; Minimum load, maximum generation and maximum load, 10 % generation scenarios.
- Time series studies with historic generation and load data from 2018.

These generation and load dispatch scenarios have been selected to demonstrate the capability of the Virtual Statcom in extreme and normal network operating conditions.

9.1. Capacity Hosting Algorithms

The Virtual Statcom generation and load hosting algorithms determine the available hosting capacity for each contingency configuration. The hosting algorithms been updated based on the feeder group approach and to incorporate improvements and resolve limitations identified in a Work Packages 2. The main development of the capacity algorithms, to accurately determine the hosting capacity, was a change to the use of automatic tap changing for transformers within each network. The hosting algorithms now allow all network transforms except the network tie transformers to operate with automatic tap changing during the Virtual Statcom algorithms.

9.2. Optimisation to Increase Generation Hosting

The Virtual Statcom algorithm has shown that little generation capacity can be release by optimising the reactive power output of existing generators.

More specifically, previous generation hosting results demonstrated that the reactive power dispatch of existing generators affects a network's generation hosting capacity. This identified that a trade-off exists between optimising to reduce thermal loading and reduce system voltages.

A method to calculate a feeder group weighting was developed and the Virtual Statcom optimisation algorithm has been updated to determine and use weighting factors for each feeder group. The aim of these feeder group weighing calculations is to determine whether a feeder group will become thermally, or voltage constrained when increasing generation and then focus the optimisation algorithm accordingly.

Analysis of the feeder group calculation has shown that although reasonably accurate in cases where there is limited additional generation hosting capacity available it is less accurate when a greater increase in generation is possible. Further investigation into this has shown that this is due to the linear approximation of non-linear bus voltages that arise when significantly increasing generation.

9.3. Optimisation to Increase Load Hosting

The Virtual Statcom has shown that load hosting capacity can be released by controlling the reactive power output of existing generators.

More specifically, the load hosting optimisation objective function has been modified to always optimise to reduce the thermal loading in the network. The results presented show that this provides increase in the load hosting capacity in a network for almost all contingency and load dispatch configurations. The Virtual Statcom is able to provide benefit as voltage and thermal constraints are not conflicting when increasing network load. There is the potential for a real time Virtual Statcom tool to improve the load hosting capacity of a network to serve the expected increases in load from electric vehicles.

9.4. Time Series Studies

Time series functionality has been added to the Virtual Statcom algorithms. At a high level the time series functionality allows the optimisation and per contingency hosting algorithms to be run for multiple load and generation scenarios.

The time series results are in line with the results obtained in the extreme operating scenarios. For the time series generation hosting results presented there are cases where the automatic feeder group weighting factor provided benefit in some configurations but not all cases. However, the time series load hosting results presented show that by optimising reactive power set points to reducing thermal loadings in a network produces a benefit under almost all system condition and configurations analysed.

9.5. Further Analysis

As presented in Work Package 2 and Work Package 4 due to the continuously changing generation and load on the system the limiting constraint in terms of generation hosting capacity is difficult to determine in advance. Therefore, the optimum solution for reactive power dispatch to increase the hosting capacity needs to operate closer to real-time in a way that the optimisation can focus on the forecasted generation / load scenario. At this point, the optimisation algorithms can be tuned to focus on either resolving the thermal or voltage issues that will become the limiting constraint for a known operating condition. The optimisation algorithms have shown that when they focus on either thermal or voltage issues exclusively, they can reliably improve these conditions, particularly where system limits are breached. Further analysis and assessment are therefore worthwhile to determine how the Virtual Statcom algorithms may be adjusted for use in different scenarios, such as:

- A real time network management tool to improve system operating conditions and resolve constraints.
- A network planning / connections assessment tool to determine capacity and options for new connections.

10. References

[1] G. McCormick, “JK7261-TR-01 Rev 04 - WPD Virtual Statcom WP1 Report,” PSC UK, Warwick, UK, 2019.

[2] Thomas, L. J., Burchill, A., Rogers, D. J., Guest, M., & Jenkins, N, “Assessing distribution network hosting capacity with the addition of soft open points,” *IET,* 2016.

[3] Al Alamat, Fadi, “"Increasing the hosting capacity of radial distribution grids in Jordan.,” 2015.

[4] Mahmud, M. A., Hossain, M. J., & Pota, H. R, “Analysis of voltage rise effect on distribution network with distributed generation,” *IFAC Proceedings Volumes,* no. 44, 2011.

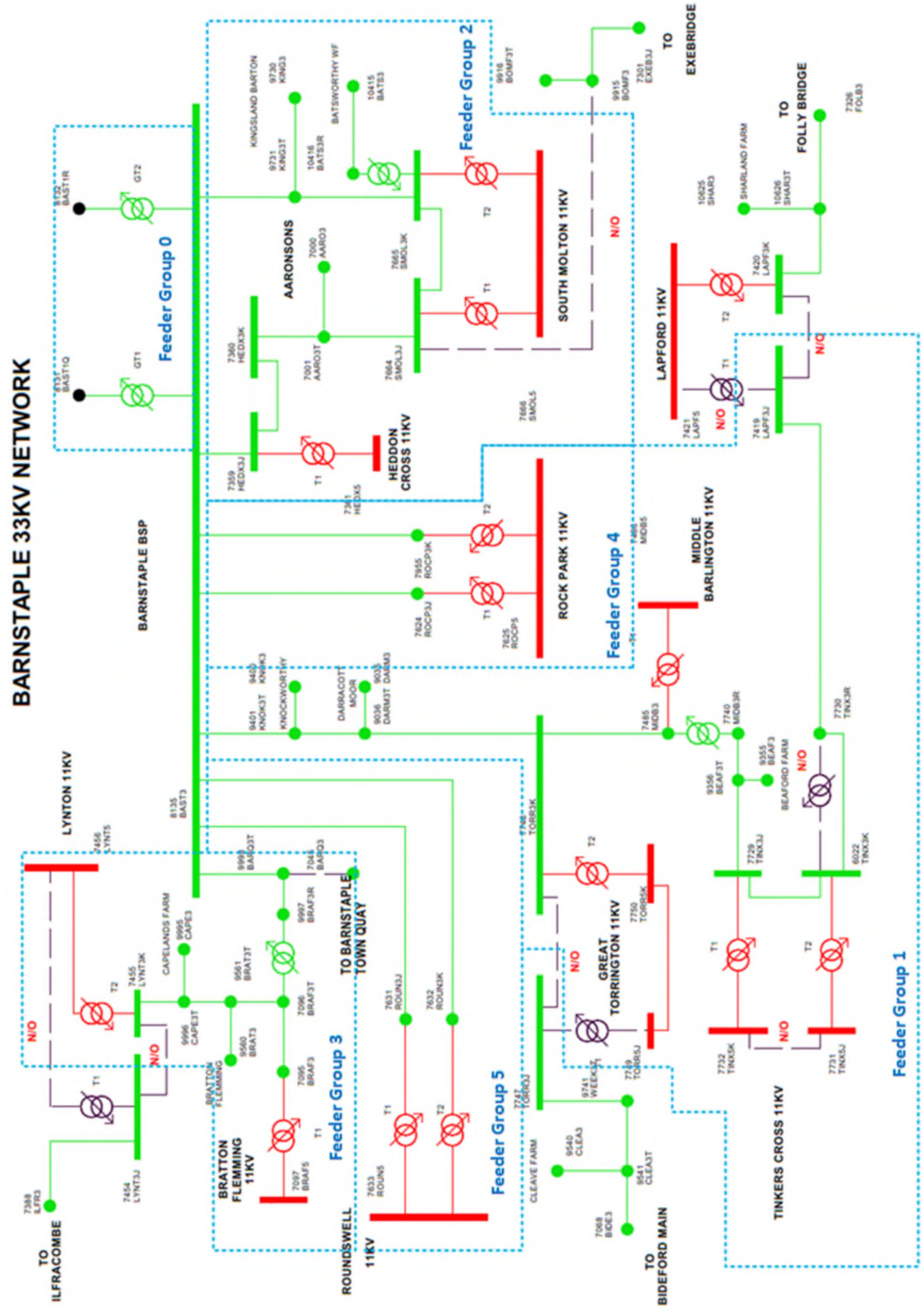
[5] G. McCormick, “JK7261-TR-03 Rev 03 - WPD Virtual Statcom WP2 Report,” PSC UK, Warwick, UK, 2019.

[6] Dent, Chris J., Luis F. Ochoa, and Gareth P. Harrison, “Network distributed generation capacity analysis using OPF with voltage step constraints,” *IEEE Transactions on Power systems,* vol. 25.1, pp. 296-304, 2010.

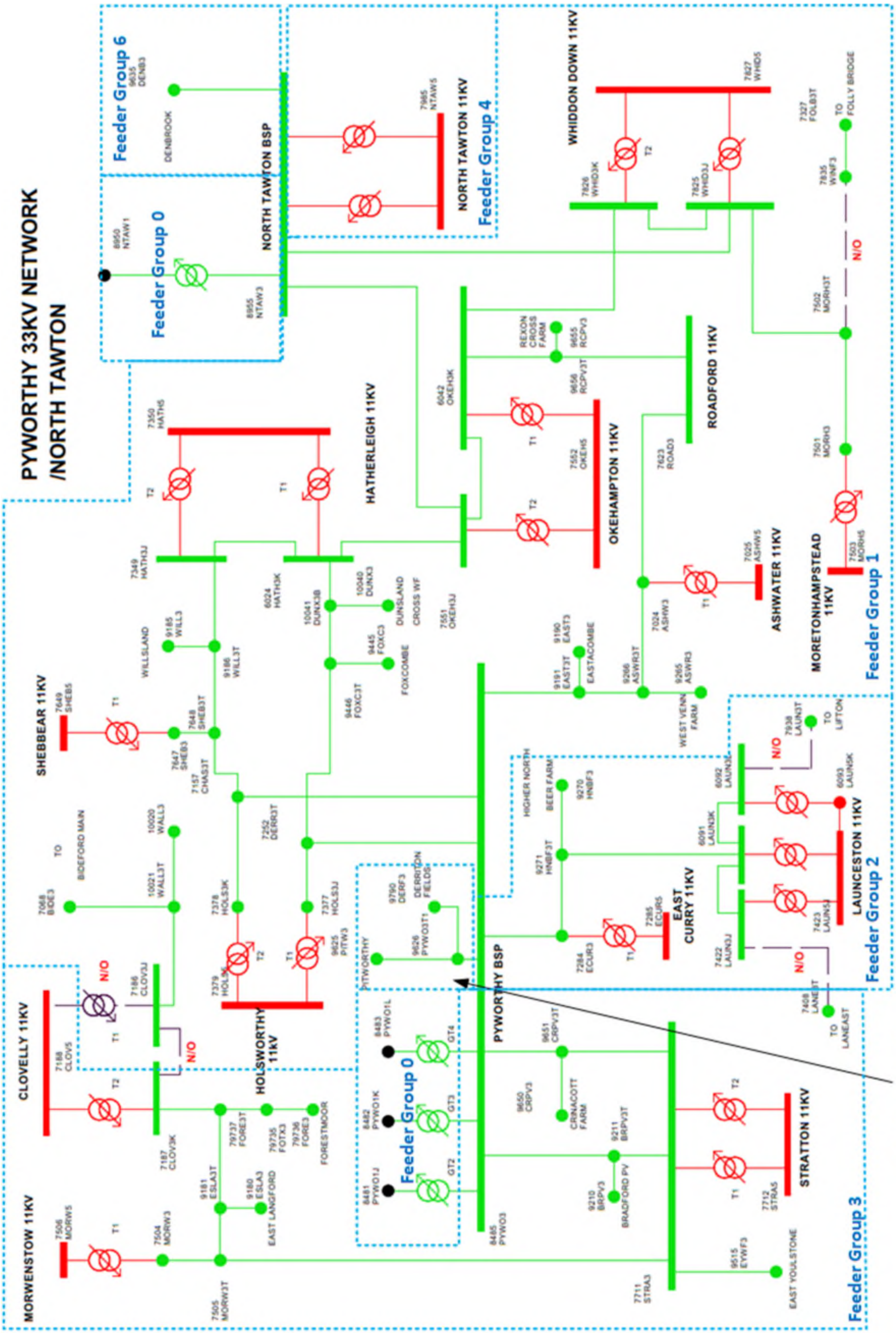
[7] Vovos, P. N., Harrison, G. P., Wallace, A. R., & Bialek, J. W., “Optimal power flow as a tool for fault level-constrained network capacity analysis,” *EEE Transactions on Power Systems,* vol. 20(2), pp. 734-741, 2005.

Appendix A Feeder groups

A.1. Barnstaple 33 kV BSP Feeder Groups



A.2. Pyworthy and North Tawton 33 kV BSP Feeder Groups



Appendix B Updated Functions and Procedures for Feeder Group Approach

B.1. Identify Feeder Groups Function

For the feeder group approach to be implemented for Virtual Statcom the algorithms need to dynamically identify the busses and branches that belong to a feeder group. An example of required output for Tiverton is shown in the figure below.

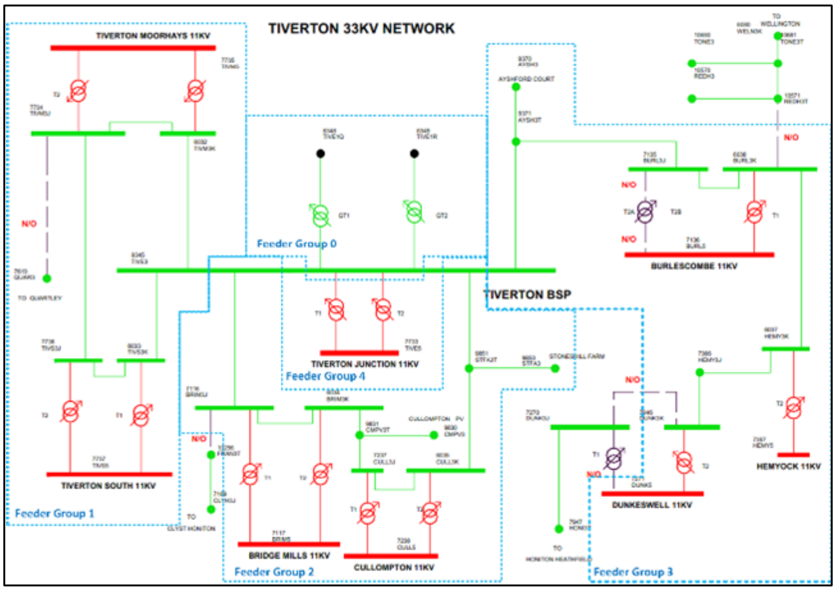


Figure 10-1 - Tiverton Feeder GroupsThe pseudo code for the function to identify the feeder groups is as follows:

Input(s): Study zone of interest

- Determine the feeders connected to the study zone BSP/Primary bus(es), i.e. the bus on the LV side of the BSP or Primary tie transformers. Bus TIVE3 8345 in the figure above.
- Remove all the feeders connected to the BSP/Primary bus.
- Determine the number of islands in the zone.
- For each island, determine the buses that are in each island – these are the feeder group buses.
- Any busses that are modelled in the selected zone in the PSSE case but not in an island are ignored as these busses have no electrical path to the main BSP/Primary bus. An example of this is bus 7406 LAUN3J2 which is assigned to Pyworthy zone 220 in the PSSE case but is modelled in the case as being supplied from bus 7408 in zone 310 (St Tudy).

Output(s): feeder group buses.

Notes:

- Feeder Group 0 will always contain the BSP/Primary bus bar network tie transformers.
- Using the feeder group buses the feeder group branches can be determined.

B.2. Initial dynamic scaling function

To reduce the number of iterations taken to find the first violation a dynamic pre-scaling algorithm has been implemented.

The pseudo code for the pre-scaling algorithm is as follows:

Input(s): Case with dummy generation/load to be scaled

- Scale feeder groups dummy generation/load up by 5 MW (this step size will be a user input) and check for violations.
- Continue with 5 MW step size until violations occur.
- Revert case to last non violation case and increase the scaling by a reduced step size of 4 MW:
    - If this case has no violations this is the starting point for the scaling.
    - If this case has violation revert to last non violation case.
- Continue with this approach until the step size is 1 MW or the smaller step size case has not violations.

Output: A PSSE case n x 1 MW away from the first violation. Where n is the number of feeder groups.

The following figure shows the algorithm operation graphically.

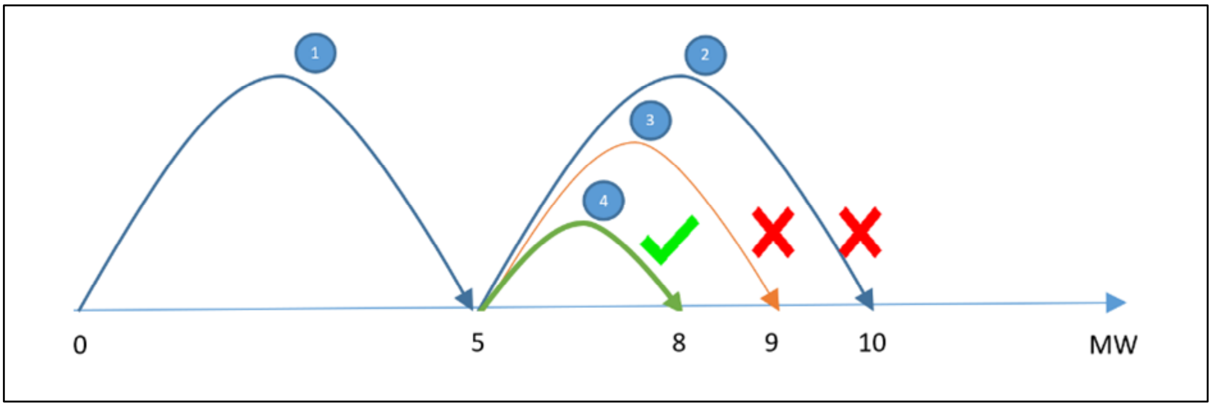


Figure 10-2 – Hosting Algorithms Initial Dynamic Scaling

Appendix C Feeder Group Hosting Capacity Results

C.1. Generation Hosting Minimum Load Maximum Generation

C.1.1. Tiverton 33 kV BSP

Network: Tiverton 33 kV BSP Load/Generation Scenario: Minimum Load Maximum Generation							
Network Configuration	Pre-optimisation generation hosting capacity	Capacity Increase (MW)			Capacity Increase %		
		Thermal	Voltage	Weighting Factor	Thermal	Voltage	Weighting Factor
intact system	103.44	-22.82	-0.82	0.66	-22.1%	-0.8%	0.6%
TIVE3_TIVE1R_G2	59.35	1.03	-0.90	0.75	1.7%	-1.5%	1.3%
TIVE3_TIVE1Q_G1	59.42	0.87	-0.87	1.09	1.5%	-1.5%	1.8%
TIVM3K_TIVE3_L1	83.66	-10.18	-2.77	-9.77	-12.2%	-3.3%	-11.7%
TIVS3K_TIVE3_L1	85.61	-8.30	0.06	2.05	-9.7%	0.1%	2.4%
BURL3J_AYSH3T_L1+ TIVE3_AYSH3T_L1+ AYSH3_AYSH3T_L1	87.87	-25.06	-0.39	0.73	-28.5%	-0.4%	0.8%
BRIM3J_TIVE3_L1	98.24	-24.93	-0.82	-27.11	-25.4%	-0.8%	-27.6%
BURL3K_HEMY3K_L1	101.27	-25.65	-0.63	-13.57	-25.3%	-0.6%	-13.4%
HEMY3K_HEMY5_T2	102.30	-26.19	-0.22	-26.19	-25.6%	-0.2%	-25.6%
HEMY3J_DUNK3K_L1	102.47	-23.73	-0.79	-17.84	-23.2%	-0.8%	-17.4%
BURL3K_BURL5_T1	102.57	-23.86	-0.81	-17.39	-23.3%	-0.8%	-17.0%
DUNK5_DUNK3K_T2	102.63	-21.11	-0.81	0.57	-20.6%	-0.8%	0.6%
CULL3K_STFA3T_L1+ TIVE3_STFA3T_L1+ STFA3_STFA3T_L1	102.65	-33.16	-0.77	0.04	-32.3%	-0.8%	0.0%
TIVM3J_TIVS3J_L1	103.15	-9.06	-0.60	0.71	-8.8%	-0.6%	0.7%
TIVM3J_WSHC3T_L1+ WSHB3_WSHC3T_L1	103.16	1.52	0.00	1.52	1.5%	0.0%	1.5%
TIVM3J_TIVM5_T2	103.41	-22.79	-0.77	0.67	-22.0%	-0.7%	0.6%
TIVM3K_TIVM5_T1	103.42	-22.80	-0.79	0.70	-22.0%	-0.8%	0.7%
TIVE5_TIVE3_T1	103.42	-22.08	-0.77	0.68	-21.4%	-0.7%	0.7%
TIVE5_TIVE3_T2	103.42	-17.11	-0.77	0.68	-16.5%	-0.7%	0.7%
TIVS3K_TIVS5_T1	103.43	-7.08	-0.81	0.65	-6.8%	-0.8%	0.6%
TIVS3J_TIVS5_T2	103.43	-22.41	-0.66	0.63	-21.7%	-0.6%	0.6%
CULL3J_CULL5_T1	103.43	-18.08	0.00	0.59	-17.5%	0.0%	0.6%
BRIM3J_BRIM5_T1	103.43	-19.08	-0.82	0.73	-18.4%	-0.8%	0.7%
CULL3K_CULL5_T2	103.43	-21.27	-0.82	0.63	-20.6%	-0.8%	0.6%
BRIM3K_BRIM5_T2	103.43	-22.81	-0.82	0.67	-22.1%	-0.8%	0.7%

BRIM3K_CMPV3T_L1+ CULL3J_CMPV3T_L1+ CMPV3_CMPV3T_L1	103.46	0.41	-9.99	0.48	0.4%	-9.7%	0.5%

C.1.2. Barnstaple 33 kV BSP

Network: Barnstaple 33 kV BSP Load/Generation Scenario: Minimum Load Maximum Generation							
Network Configuration	Pre-optimisation generation hosting capacity	Capacity Increase (MW)			Capacity Increase %		
		Thermal	Voltage	Weighting Factor	Thermal	Voltage	Weighting Factor
intact system	130.03	0.91	-1.29	1.23	0.7%	-1.0%	0.9%
SMOL3K_KING3T_L1+ BAST3_KING3T_L1+ KING3_KING3T_L1	55.42	0.00	0.00	0.00	0.0%	0.0%	0.0%
HEDX3J_BAST3_L1	60.42	70.31	22.45	43.79	116.4%	37.1%	72.5%
AARO3_AARO3T_L1+ AARO3T_HEDX3K_L1+ AARO3T_SMOL3J_L1	60.42	0.00	0.00	0.00	0.0%	0.0%	0.0%
BAST1Q_BAST3_G1	70.80	0.00	-2.83	1.46	0.0%	-4.0%	2.1%
BAST1R_BAST3_G2	70.82	0.00	-2.61	0.77	0.0%	-3.7%	1.1%
TORR3K_DARM3T_L1+ DARM3_DARM3T_L1+ DARM3T_KNOK3T_L1+ BAST3_KNOK3T_L1+ KNOK3_KNOK3T_L1	126.68	0.00	0.00	1.24	0.0%	0.0%	1.0%
MIDB3_TORR3K_L1	128.13	1.99	-0.61	0.60	1.6%	-0.5%	0.5%
BAST3_BARQ3T_L1+ BRAF3R_BARQ3T_L1	128.17	0.00	0.00	2.03	0.0%	0.0%	1.6%
LYNT3K_CAPE3T_L1+ BRAT3T_CAPE3T_L1+ CAPE3_CAPE3T_L1+ BRAF3_BRAF3T_L1+ BRAF3T_BRAT3T_L1+ BRAT3_BRAT3T_L1	128.29	1.91	0.00	1.80	1.5%	0.0%	1.4%
BRAF3T_BRAF3R_R1	128.29	1.90	0.30	1.97	1.5%	0.2%	1.5%
MIDB3_MIDB3R_R1	128.63	1.76	-1.07	1.06	1.4%	-0.8%	0.8%
TINX3J_BEAF3T_L1+ MIDB3R_BEAF3T_L1+ BEAF3_BEAF3T_L1	128.63	0.00	2.51	2.57	0.0%	2.0%	2.0%
TORR3K_TORR5K_T2	128.83	0.00	0.00	1.41	0.0%	0.0%	1.1%
LYNT3K_LYNT5_T2	129.33	1.39	-1.62	1.09	1.1%	-1.3%	0.8%
TINX3J_TINX5K_T1	129.34	0.00	0.00	0.73	0.0%	0.0%	0.6%
BRAF3_BRAF5_T1	129.51	1.31	-1.51	1.37	1.0%	-1.2%	1.1%

TINX3K_TINX5J_T2	129.56	1.42	-1.28	1.18	1.1%	-1.0%	0.9%
ROCP3J_BAST3_L1	129.58	1.53	-1.47	0.67	1.2%	-1.1%	0.5%
MIDB3_MIDB5_T1	129.60	1.25	-1.38	1.23	1.0%	-1.1%	0.9%
HEDX3J_HEDX5_T1	129.60	0.93	-1.70	1.52	0.7%	-1.3%	1.2%
ROCP3K_BAST3_L2	129.67	1.48	-1.71	1.38	1.1%	-1.3%	1.1%
ROUN3K_BAST3_L2	130.00	1.18	-0.60	1.03	0.9%	-0.5%	0.8%
ROUN3J_BAST3_L1	130.01	1.46	-0.76	1.65	1.1%	-0.6%	1.3%
ROUN3K_ROUN5_T2	130.02	0.16	-1.49	2.07	0.1%	-1.1%	1.6%
ROUN3J_ROUN5_T1	130.02	0.99	-1.44	1.56	0.8%	-1.1%	1.2%
ROCP5_ROCP3K_T2	130.02	-0.46	-1.60	0.68	-0.4%	-1.2%	0.5%
LAPF3J_TINX3R_L1	130.02	1.39	-1.38	1.12	1.1%	-1.1%	0.9%
ROCP3J_ROCP5_T1	130.03	1.32	-0.31	1.55	1.0%	-0.2%	1.2%
SMOL3K_SMOL5_T2	130.03	0.88	-1.63	1.17	0.7%	-1.3%	0.9%
SMOL3J_SMOL5_T1	130.03	1.32	-1.44	0.68	1.0%	-1.1%	0.5%
BATS3_BATS3R_L1	130.96	0.78	0.49	0.57	0.6%	0.4%	0.4%
SMOL3K_BATS3R_R1	130.96	0.07	-1.80	-0.93	0.1%	-1.4%	-0.7%

C.1.3. Pyworthy and North Tawton 33 kV BSPs

Network: Pyworthy and North Tawton 33 kV BSP Load/Generation Scenario: Minimum Load Maximum Generation							
Network Configuration	Pre-optimisation generation hosting capacity	Capacity Increase (MW)			Capacity Increase %		
		Thermal	Voltage	Calculated Weighting Factor	Thermal	Voltage	Calculated Weighting Factor
intact system	244.36	-7.36	-19.70	-30.33	-3.0%	-8.1%	-12.4%
NTAW1_NTAW3_G1	146.91	0.00	0.00	0.00	0.0%	0.0%	0.0%
STRA3_BRPV3T_L1+ PYWO3_BRPV3T_L1+ BRPV3_BRPV3T_L1	206.75	7.84	0.00	-25.92	3.8%	0.0%	-12.5%
STRA3_CRPV3T_L1+ PYWO3_CRPV3T_L1+ CRPV3_CRPV3T_L1	206.78	4.13	0.00	-7.14	2.0%	0.0%	-3.5%
LAUN3K_HNBF3T_L2+ ECUR3_HNBF3T_L2+ HNBF3_HNBF3T_L1	208.44	20.39	0.00	11.50	9.8%	0.0%	5.5%
PITW3_PYWO3T1_L1	208.73	5.33	3.16	-10.15	2.6%	1.5%	-4.9%
PYWO3T1_DERF3_L1	208.82	-5.53	-7.39	-6.01	-2.7%	-3.5%	-2.9%
ECUR3_PYWO3_L1	209.12	3.52	-14.44	6.44	1.7%	-6.9%	3.1%
HATH3J_WILL3T_L1+ SHEB3T_WILL3T_L1+ WILL3_WILL3T_L1+ CHAS3T_HOLS3K_L1+	211.01	-3.07	0.00	-3.82	-1.5%	0.0%	-1.8%

CHAS3T_SHEB3T_L1+ CHAS3T_PYWO3_L1+ SHEB3_SHEB3T_L1							
ASHW3_ASWR3T_L1+ EAST3T_ASWR3T_L1+ ASWR3_ASWR3T_L1+ PYWO3_EAST3T_L1+ EAST3_EAST3T_L1	211.12	-3.51	0.00	-5.93	-1.7%	0.0%	-2.8%
PYWO1K_PYWO3_G3	216.50	25.50	0.00	12.81	11.8%	0.0%	5.9%
DERR3T_FOXC3T_L1+ FOXC3_FOXC3T_L1+ FOXC3T_DUNX3B_L1+ DERR3T_HOLS3J_L1+ DERR3T_PYWO3_L1	218.03	-2.59	0.00	-7.45	-1.2%	0.0%	-3.4%
NTAW3_DENB3_L1	218.25	1.72	-7.39	-4.67	0.8%	-3.4%	-2.1%
OKEH3K_RCPV3T_L1+ ROAD3_RCPV3T_L1+ RCPV3_RCPV3T_L1	218.58	-5.20	0.00	-2.30	-2.4%	0.0%	-1.1%
OKEH3J_NTAW3_L1	221.62	-4.55	-9.64	-6.86	-2.1%	-4.4%	-3.1%
ASHW3_ASHW5_T1	223.44	-0.01	2.95	-10.61	0.0%	1.3%	-4.7%
OKEH3K_WHID3K_L1	224.18	1.15	-11.88	-9.40	0.5%	-5.3%	-4.2%
WHID3J_NTAW3_L1	224.19	11.43	-10.51	1.71	5.1%	-4.7%	0.8%
HATH3K_DUNX3B_L1	224.59	-12.73	-14.91	11.80	-5.7%	-6.6%	5.3%
MORW3_MORW5_T1	225.06	2.78	-7.23	-0.45	1.2%	-3.2%	-0.2%
FOTX3_FORE3_L1	225.87	-5.67	-9.70	-6.59	-2.5%	-4.3%	-2.9%
HOLS3K_HOLS5_T2	227.47	-9.56	-14.39	-20.45	-4.2%	-6.3%	-9.0%
STRA3_EYWF3_L1	227.48	8.95	1.34	-8.49	3.9%	0.6%	-3.7%
LAUN3L_LAUN5K_T3	232.08	-1.45	2.74	-8.93	-0.6%	1.2%	-3.8%
CLOV3K_FORE3T_L1+ ESLA3T_FORE3T_L2+ FORE3_FORE3T_L2+ MORW3_MORW3T_L1+ MORW3T_STRA3_L1+ MORW3T_ESLA3T_L1+ ESLA3_ESLA3T_L1	232.67	7.19	0.00	-16.03	3.1%	0.0%	-6.9%
CLOV3K_CLOV5_T2	234.10	0.17	-9.27	-13.96	0.1%	-4.0%	-6.0%
ECUR3_ECUR5_T1	235.08	-4.26	-23.37	2.98	-1.8%	-9.9%	1.3%
PYWO1J_PYWO3_G2	236.35	3.63	0.00	-4.37	1.5%	0.0%	-1.8%
PYWO1L_PYWO3_G4	236.35	3.69	0.00	-2.71	1.6%	0.0%	-1.1%
HATH3K_OKEH3J_L1	237.85	-16.19	-29.01	-24.57	-6.8%	-12.2%	-10.3%
HOLS3J_HOLS5_T1	239.81	0.74	-6.91	-24.40	0.3%	-2.9%	-10.2%
MORH3_MORH3T_L1+ MORH3T_WHID3J_L1	239.93	-15.39	0.00	-7.99	-6.4%	0.0%	-3.3%
ASHW3_ROAD3_L1	241.92	2.66	-12.88	-3.74	1.1%	-5.3%	-1.5%
SHEB3_SHEB5_T1	243.03	-26.25	-6.03	-21.41	-10.8%	-2.5%	-8.8%
MORH3_MORH5_T1	243.93	-30.37	-14.72	-6.91	-12.5%	-6.0%	-2.8%
OKEH3K_OKEH5_T1	244.32	1.07	-32.25	-3.62	0.4%	-13.2%	-1.5%
OKEH3J_OKEH5_T2	244.32	0.26	-20.46	-27.66	0.1%	-8.4%	-11.3%

NTAW5_NTAW3_T1	244.35	0.46	-18.01	-22.02	0.2%	-7.4%	-9.0%
NTAW5_NTAW3_T2	244.35	0.02	-8.50	-13.80	0.0%	-3.5%	-5.6%
HATH3K_HATH5_T1	244.35	-20.82	-9.97	-29.62	-8.5%	-4.1%	-12.1%
HATH3J_HATH5_T2	244.35	-20.72	-6.76	-20.55	-8.5%	-2.8%	-8.4%
LAUN3K_LAUN5J_T1	244.36	-26.15	-9.46	-26.72	-10.7%	-3.9%	-10.9%
LAUN3J_LAUN5J_T2	244.36	-27.28	-8.18	-5.15	-11.2%	-3.3%	-2.1%
STRA3_STRA5_T1	244.36	-20.10	-8.54	-21.37	-8.2%	-3.5%	-8.7%
STRA3_STRA5_T2	244.36	-3.22	-7.91	-22.21	-1.3%	-3.2%	-9.1%
WHID3K_WHID5_T2	244.36	-25.03	-5.93	-13.17	-10.2%	-2.4%	-5.4%
WHID3J_WHID5_T1	244.36	-0.79	-25.32	-22.63	-0.3%	-10.4%	-9.3%

C.1.4. Tiverton Moorhayes 11kV Primary

Network: Tiverton Moorhayes 11 kV Primary Load/Generation Scenario: Minimum Load Maximum Generation							
Network Configuration	Pre-optimisation generation hosting capacity	Capacity Increase (MW)			Capacity Increase %		
		Thermal	Voltage	Calculated Weighting Factor	Thermal	Voltage	Calculated Weighting Factor
intact system	22.98	0.07	0.00	0.06	0.3%	0.0%	0.3%
TIVM3J__T1	12.37	0.12	0.00	0.00	0.9%	0.0%	0.0%
TIVM3J__T2	12.37	0.12	0.00	0.00	1.0%	0.0%	0.0%
7735_95911_1	22.15	0.03	0.00	0.03	0.1%	0.0%	0.1%
7735_95167_1	22.68	0.09	0.00	0.08	0.4%	0.0%	0.4%
7735_95000_1	22.69	0.06	0.00	0.00	0.2%	0.0%	0.0%
7735_95813_1	22.72	0.05	0.00	0.05	0.2%	0.0%	0.2%
7735_95755_1	22.75	0.09	0.00	0.09	0.4%	0.0%	0.4%
7735_95785_1	23.03	0.07	0.00	0.03	0.3%	0.0%	0.1%

C.2. Load Hosting Maximum Load 10% Generation

C.2.1. Tiverton 33 kV BSP

Network: Tiverton 33 kV BSP Load/Generation Scenario: Maximum Load 10% Generation			
Network Configuration	Pre-optimisation Load hosting capacity	Capacity Increase (MW)	Capacity Increase %
intact system	77.87	11.57	14.9%
TIVM3K_TIVE3_L1	76.37	6.61	8.7%
TIVS3K_TIVE3_L1	76.62	8.88	11.6%
BURL3K_HEMY3K_L1	84.46	7.15	8.5%
BRIM3J_TIVE3_L1	77.35	9.61	12.4%
HEMY3J_DUNK3K_L1	85.43	7.78	9.1%
TIVM3J_TIVS3J_L1	77.88	10.37	13.3%
TIVM3K_TIVM5_T1	77.07	11.11	14.4%
TIVS3K_TIVS5_T1	77.40	9.43	12.2%
BRIM3K_BRIM5_T2	77.87	10.64	13.7%
CULL3K_CULL5_T2	77.67	10.06	13.0%
BURL3K_BURL5_T1	82.70	8.58	10.4%
HEMY3K_HEMY5_T2	84.98	7.33	8.6%
BRIM3J_BRIM5_T1	77.87	10.65	13.7%
CULL3J_CULL5_T1	77.67	10.45	13.5%
DUNK5_DUNK3K_T2	85.82	6.95	8.1%
TIVE5_TIVE3_T1	75.60	9.19	12.2%
TIVE5_TIVE3_T2	75.49	10.94	14.5%
TIVM3J_TIVM5_T2	77.07	0.00	0.0%
TIVS3J_TIVS5_T2	77.40	9.36	12.1%
TIVE3_TIVE1Q_G1	63.77	2.98	4.7%
TIVE3_TIVE1R_G2	61.17	5.31	8.7%
CULL3K_STFA3T_L1+TIVE3_STFA3T_L1+ STFA3_STFA3T_L1	49.47	18.70	37.8%
BRIM3K_CMPV3T_L1+CULL3J_CMPV3T_L1+ CMPV3_CMPV3T_L1	77.67	8.47	10.9%
BURL3J_AYSH3T_L1+TIVE3_AYSH3T_L1+ AYSH3_AYSH3T_L1	80.63	5.10	6.3%
TIVM3J_WSHC3T_L1+WSHB3_WSHC3T_L1	77.57	8.46	10.9%

C.2.2. Barnstaple 33 kV BSP

Network: Barnstaple 33 kV BSP Load/Generation Scenario: Maximum Load 10% Generation			
Network Configuration	Pre-optimisation Load hosting capacity	Capacity Increase (MW)	Capacity Increase %
intact system	53.98	18.24	34%
BAST1Q_BAST3_G1	48.38	16.10	33%
BAST1R_BAST3_G2	50.18	13.90	28%
BAST3_BARQ3T_L1+BRAF3R_BARQ3T_L1	52.07	21.80	42%
BATS3_BATS3R_L1	52.31	36.82	70%
SMOL3K_BATS3R_R1	52.31	36.04	69%
ROUN3J_BAST3_L1	52.78	26.74	51%
ROUN3K_BAST3_L2	52.78	28.00	53%
BRAF3T_BRAF3R_R1	52.83	34.82	66%
LYNT3K_CAPE3T_L1+BRAT3T_CAPE3T_L1+ CAPE3_CAPE3T_L1+BRAF3_BRAF3T_L1+ BRAF3T_BRAT3T_L1+BRAT3_BRAT3T_L1	52.83	34.52	65%
HEDX3J_BAST3_L1	52.88	39.53	75%
SMOL3K_KING3T_L1+BAST3_KING3T_L1+ KING3_KING3T_L1	52.98	17.94	34%
ROUN3J_ROUN5_T1	52.98	27.47	52%
ROCP5_ROCP3K_T2	52.98	39.24	74%
AARO3_AARO3T_L1+AARO3T_HEDX3K_L1+ AARO3T_SMOL3J_L1	53.00	39.79	75%
ROUN3K_ROUN5_T2	53.04	29.20	55%
ROCP3J_BAST3_L1	53.24	29.38	55%
ROCP3J_ROCP5_T1	53.24	37.67	71%
ROCP3K_BAST3_L2	53.34	29.33	55%
BRAF3_BRAF5_T1	53.58	27.02	50%
LYNT3K_LYNT5_T2	53.59	41.45	77%
LAPF3J_TINX3R_L1	53.71	23.61	44%
SMOL3J_SMOL5_T1	53.71	41.32	77%
SMOL3K_SMOL5_T2	53.71	24.67	46%
HEDX3J_HEDX5_T1	53.78	40.77	76%
TINX3K_TINX5J_T2	63.72	34.04	53%
MIDB3_MIDB5_T1	63.77	36.32	57%
TORR3K_TORR5K_T2	68.50	29.35	43%
TINX3J_TINX5K_T1	69.25	28.51	41%
TORR3K_DARM3T_L1+DARM3_DARM3T_L1+ DARM3T_KNOK3T_L1+BAST3_KNOK3T_L1+ KNOK3_KNOK3T_L1	80.94	7.36	9%
MIDB3_MIDB3R_R1	81.75	7.73	9%
TINX3J_BEAF3T_L1+MIDB3R_BEAF3T_L1+ BEAF3_BEAF3T_L1	81.75	16.90	21%
MIDB3_TORR3K_L1	83.98	14.59	17%

C.2.3. Pyworthy and North Tawton 33 kV BSP

Network: Pyworthy and North Tawton 33 kV BSP Load/Generation Scenario: Maximum Load 10% Generation			
Network Configuration	Pre-optimisation Load hosting capacity	Capacity Increase (MW)	Capacity Increase %
intact system	125.91	32.40	26%
NTAW1_NTAW3_G1	88.00	23.33	27%
WHID3J_NTAW3_L1	104.98	32.96	31%
PYWO1K_PYWO3_G3	105.25	53.06	50%
PYWO1J_PYWO3_G2	105.42	51.96	49%
PYWO1L_PYWO3_G4	105.42	51.70	49%
NTAW5_NTAW3_T1	110.50	46.60	42%
NTAW5_NTAW3_T2	110.50	37.01	33%
ECUR3_PYWO3_L1	117.88	32.03	27%
ASHW3_ASHW5_T1	120.59	42.24	35%
OKEH3K_OKEH5_T1	120.84	36.03	30%
OKEH3J_OKEH5_T2	120.84	26.66	22%
HATH3J_HATH5_T2	120.84	34.41	28%
HATH3K_OKEH3J_L1	120.99	39.23	32%
NTAW3_DENB3_L1	121.82	31.99	26%
ASHW3_ASWR3T_L1+EAST3T_ASWR3T_L1+ ASWR3_ASWR3T_L1+PYWO3_EAST3T_L1+ EAST3_EAST3T_L1	122.09	29.49	24%
LAUN3K_HNBF3T_L2+ECUR3_HNBF3T_L2+ HNBF3_HNBF3T_L1	122.27	25.39	21%
HATH3J_WILL3T_L1+SHEB3T_WILL3T_L1+ WILL3_WILL3T_L1+CHAS3T_HOLS3K_L1+ CHAS3T_SHEB3T_L1+CHAS3T_PYWO3_L1+ SHEB3_SHEB3T_L1	122.50	19.83	16%
DERR3T_FOXC3T_L1+FOXC3_FOXC3T_L1+ FOXC3T_DUNX3B_L1+DERR3T_HOLS3J_L1+ DERR3T_PYWO3_L1	123.16	20.94	17%
OKEH3J_NTAW3_L1	123.69	28.98	23%
CLOV3K_FORE3T_L1+ESLA3T_FORE3T_L2+ FORE3_FORE3T_L2+MORW3_MORW3T_L1+ MORW3T_STRA3_L1+MORW3T_ESLA3T_L1+ ESLA3_ESLA3T_L1	123.75	24.84	20%
HATH3K_DUNX3B_L1	123.82	27.87	23%
ASHW3_ROAD3_L1	123.93	28.62	23%
LAUN3L_LAUN5K_T3	124.37	21.19	17%
STRA3_CRPV3T_L1+PYWO3_CRPV3T_L1+ CRPV3_CRPV3T_L1	124.41	25.58	21%
MORW3_MORW5_T1	124.57	25.37	20%
STRA3_BRPV3T_L1+PYWO3_BRPV3T_L1+ BRPV3_BRPV3T_L1	124.58	15.98	13%

PITW3_PYWO3T1_L1	124.78	31.20	25%
HOLS3J_HOLS5_T1	124.84	31.64	25%
OKEH3K_RCPV3T_L1+ROAD3_RCPV3T_L1+ RCPV3_RCPV3T_L1	124.89	34.34	27%
HOLS3K_HOLS5_T2	125.02	27.98	22%
LAUN3K_LAUN5J_T1	125.05	36.70	29%
LAUN3J_LAUN5J_T2	125.05	30.46	24%
PYWO3T1_DERF3_L1	125.18	30.53	24%
ECUR3_ECUR5_T1	125.21	30.69	25%
STRA3_STRA5_T1	125.29	29.45	24%
STRA3_STRA5_T2	125.29	25.20	20%
CLOV3K_CLOV5_T2	125.44	37.27	30%
STRA3_EYWF3_L1	125.45	32.63	26%
SHEB3_SHEB5_T1	125.48	23.94	19%
FOTX3_FORE3_L1	125.74	26.27	21%
OKEH3K_WHID3K_L1	125.82	24.61	20%
WHID3K_WHID5_T2	126.16	30.72	24%
WHID3J_WHID5_T1	126.16	31.73	25%
HATH3K_HATH5_T1	126.27	35.60	28%
MORH3_MORH3T_L1+MORH3T_WHID3J_L1	127.06	20.82	16%
MORH3_MORH5_T1	127.16	33.83	27%

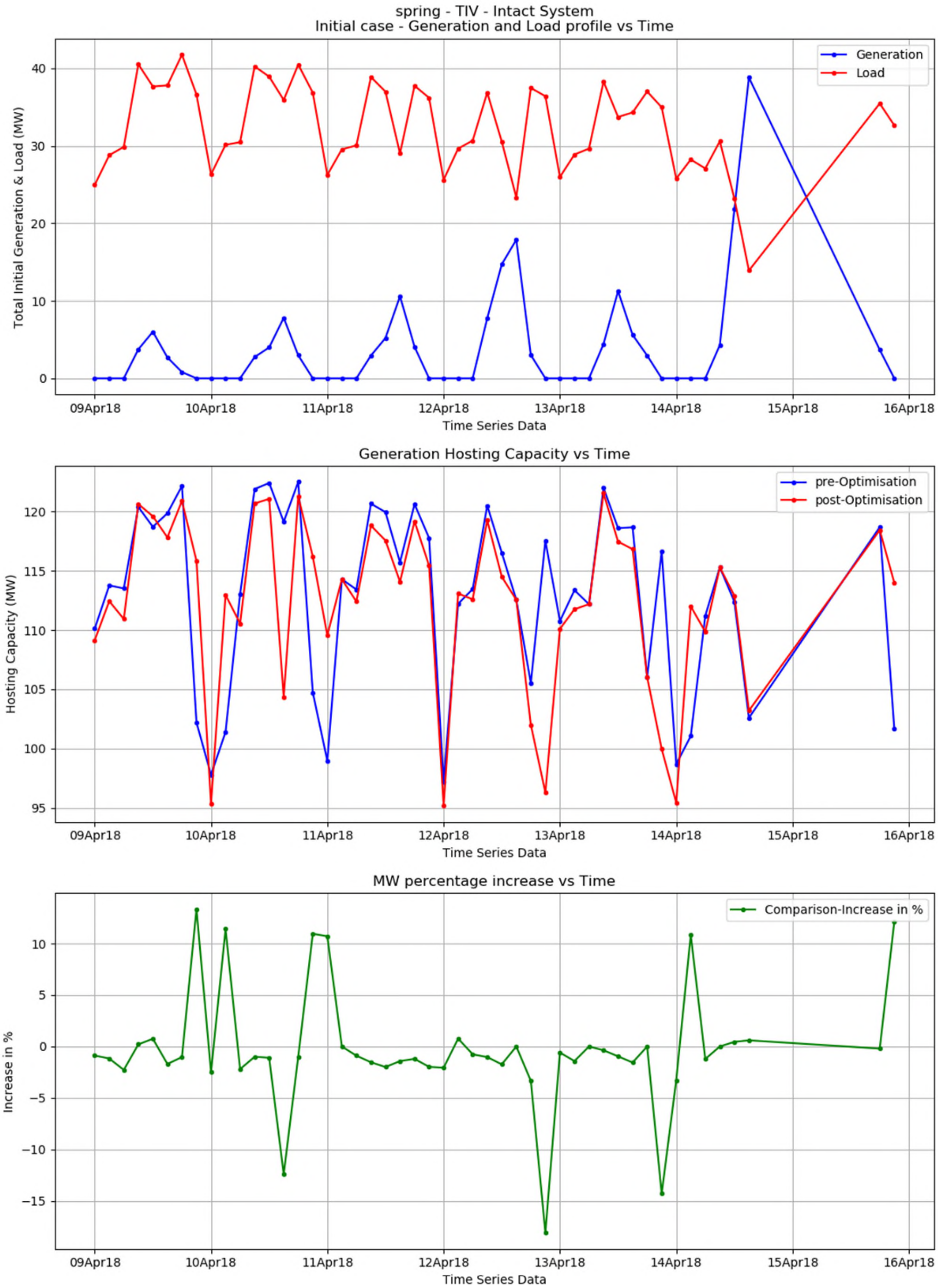
C.2.4. Tiverton Moorhayes 11kV Primary

Network: Tiverton Moorhayes 11 kV Primary Load/Generation Scenario: Maximum Load 10% Generation			
Network Configuration	Pre-optimisation Load hosting capacity	Capacity Increase (MW)	Capacity Increase %
intact system	11.37	0.00	0%
7735_95167_1	5.92	0.00	0%
7735_95755_1	6.24	0.00	0%
TIVM3J__T2	6.37	0.00	0%
7735_95000_1	6.67	0.00	0%
TIVM3J__T1	7.62	0.00	0%
7735_95785_1	7.69	0.00	0%
7735_95813_1	9.44	0.00	0%
7735_95911_1	25.94	0.01	0%

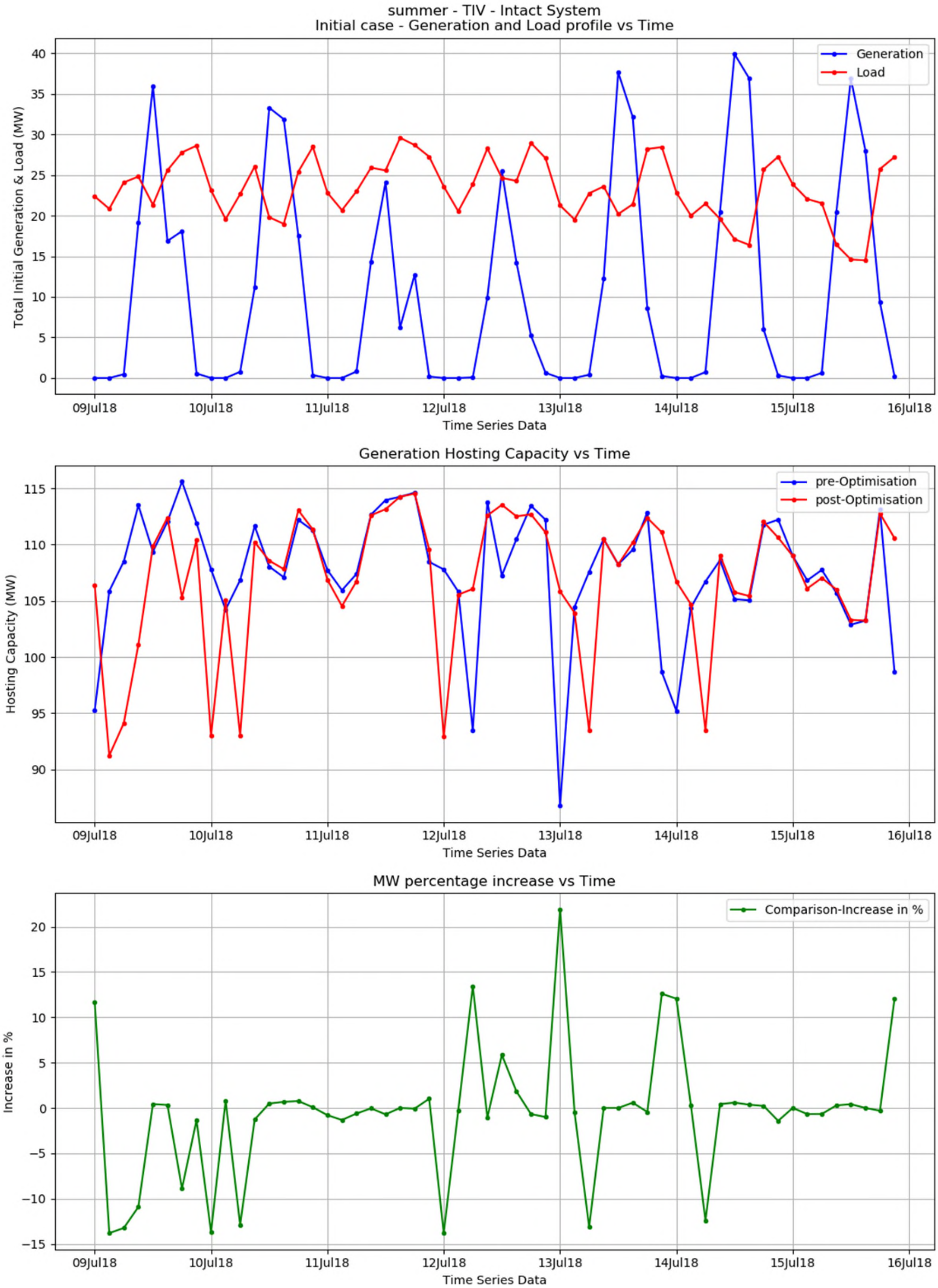
Appendix D Time Series Studies Generation Hosting Results

D.1. Tiverton 33 kV BSP

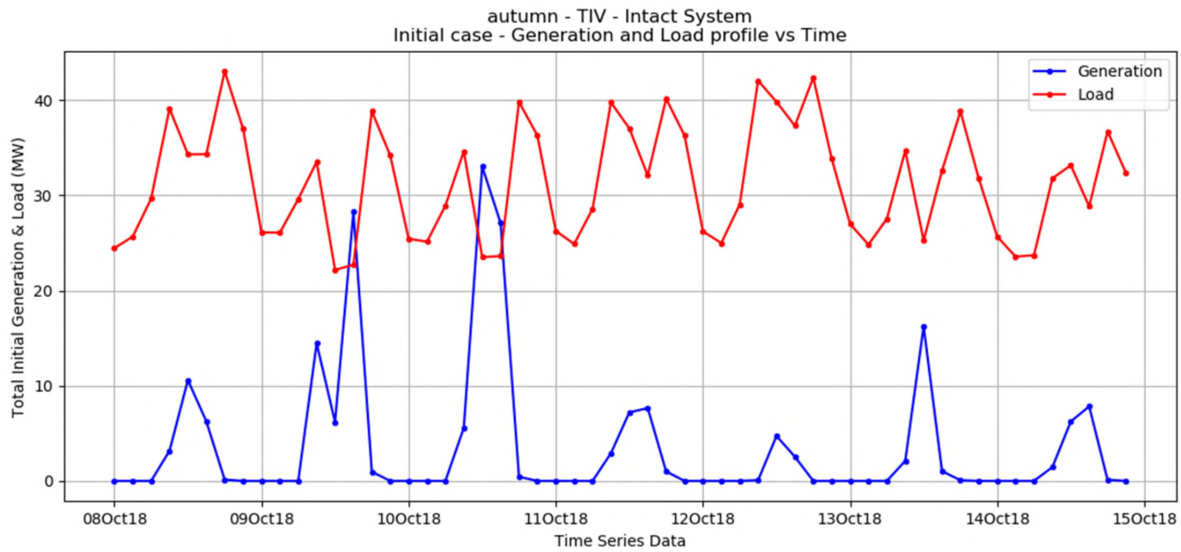
D.1.1. Intact System Spring Week

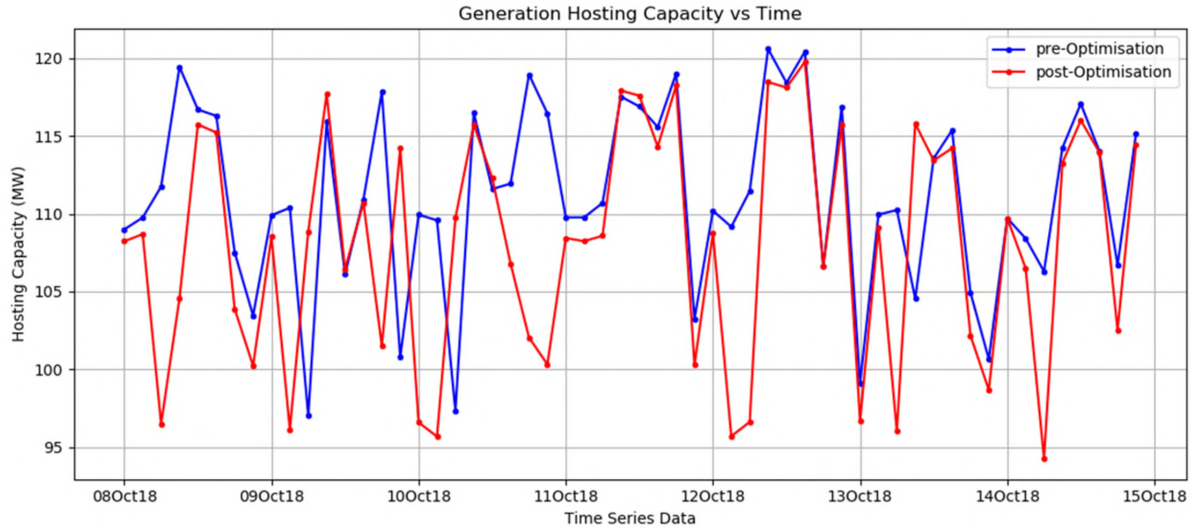


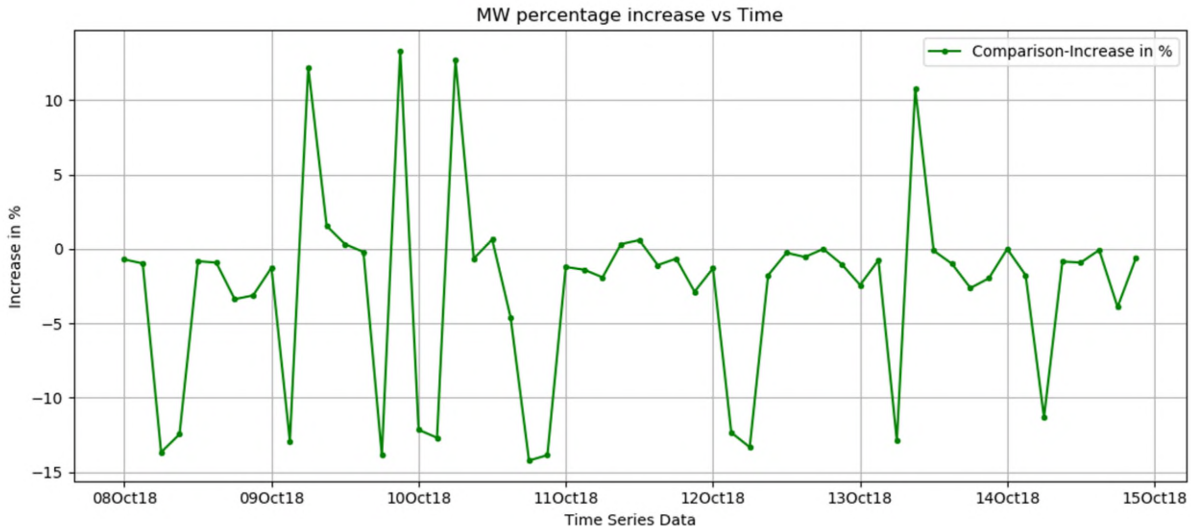
D.1.2. Intact System Summer Week



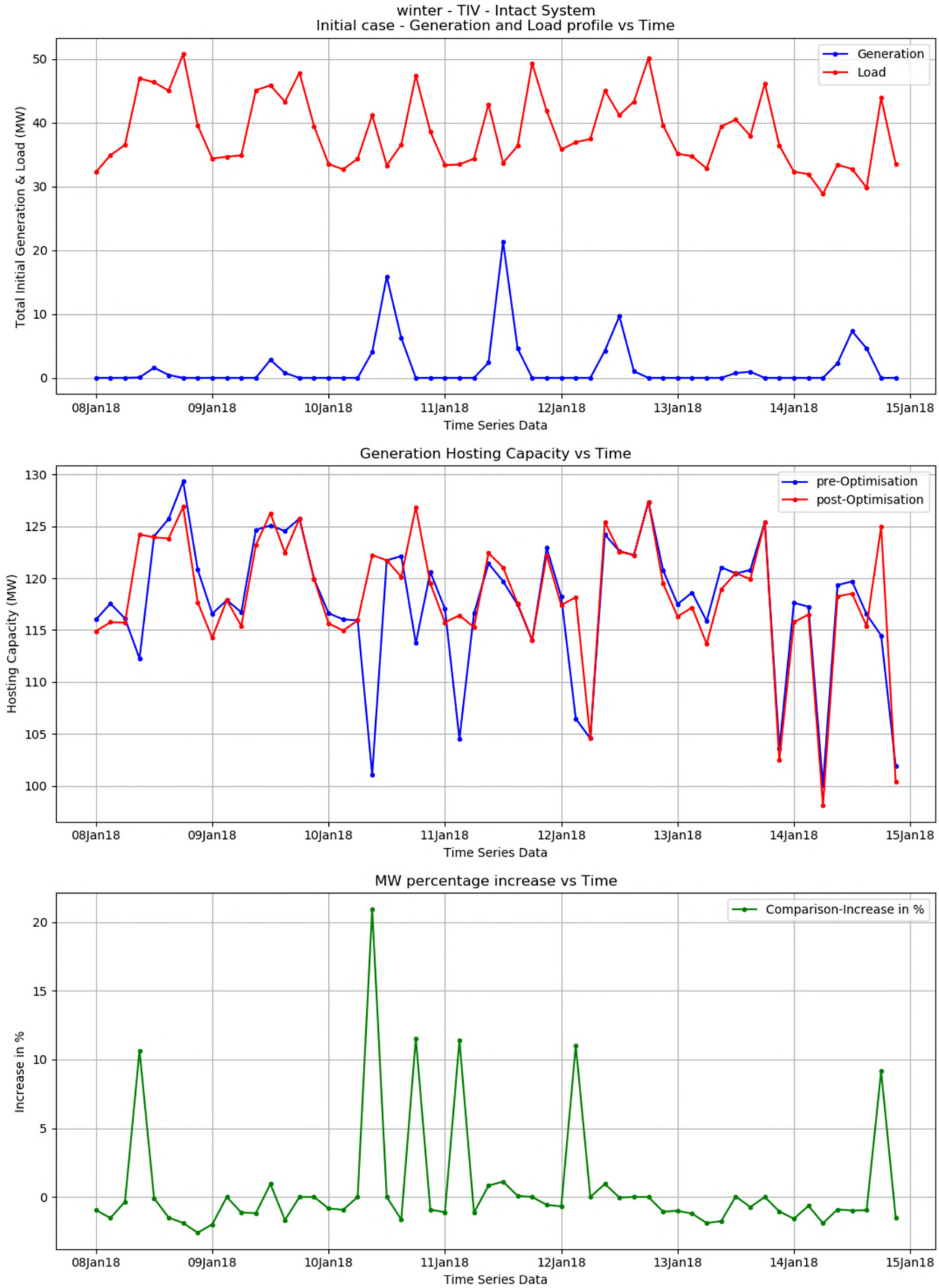
D.1.3. Intact System Autumn Week



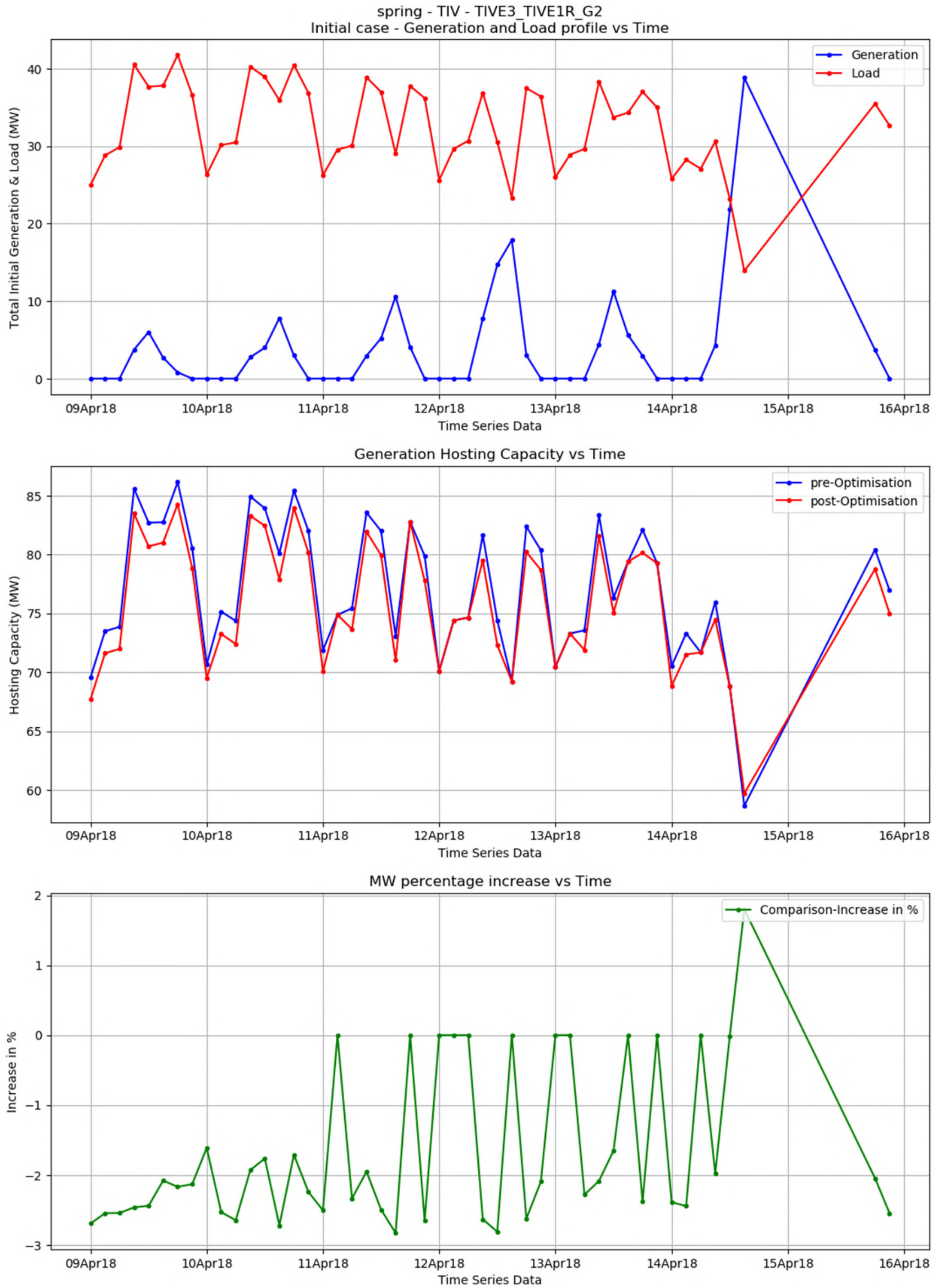




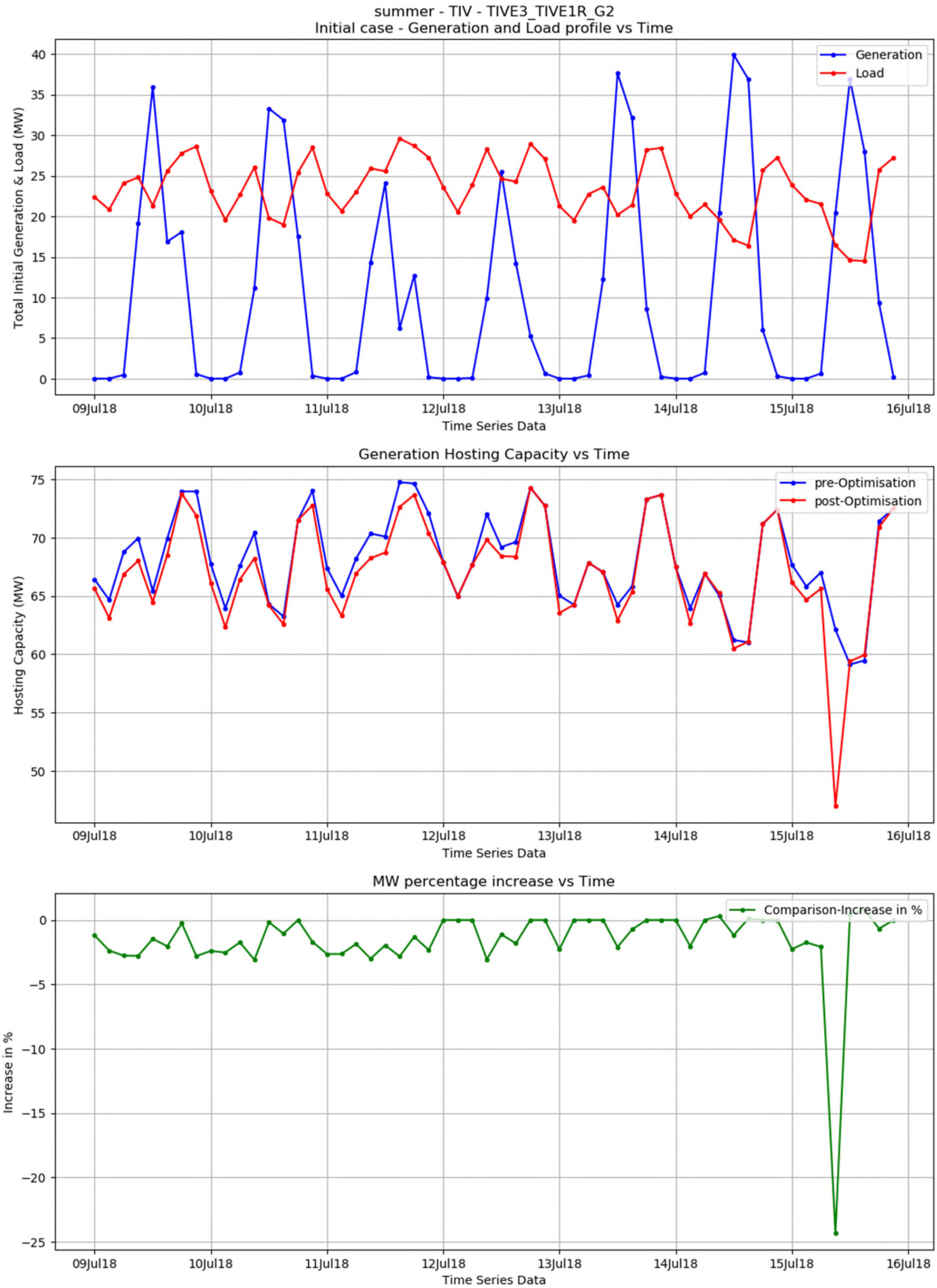
D.1.4. Intact System Winter Week



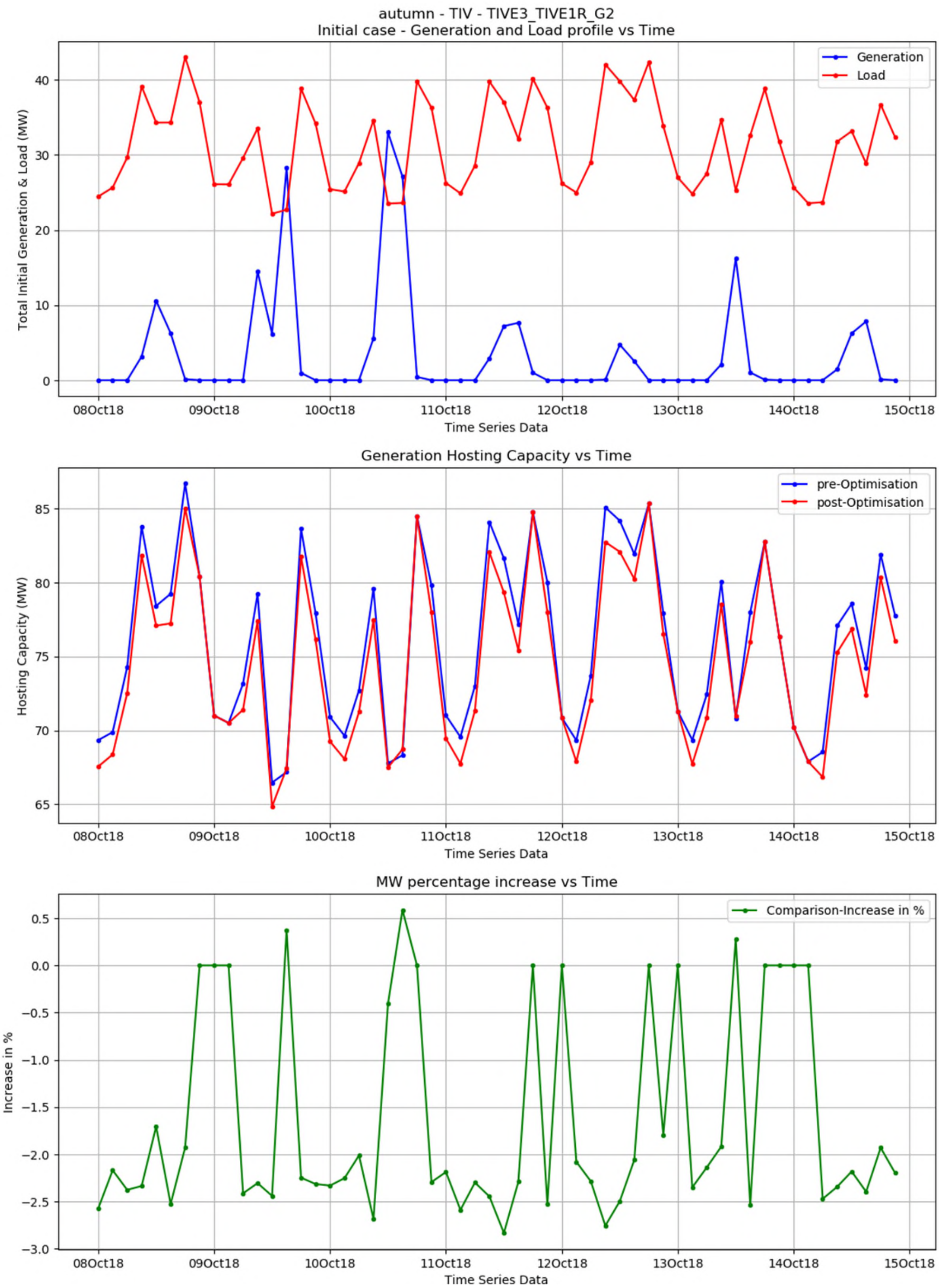
D.1.5. Worst contingency TIVE3_TIVE1R_G2 Spring Week



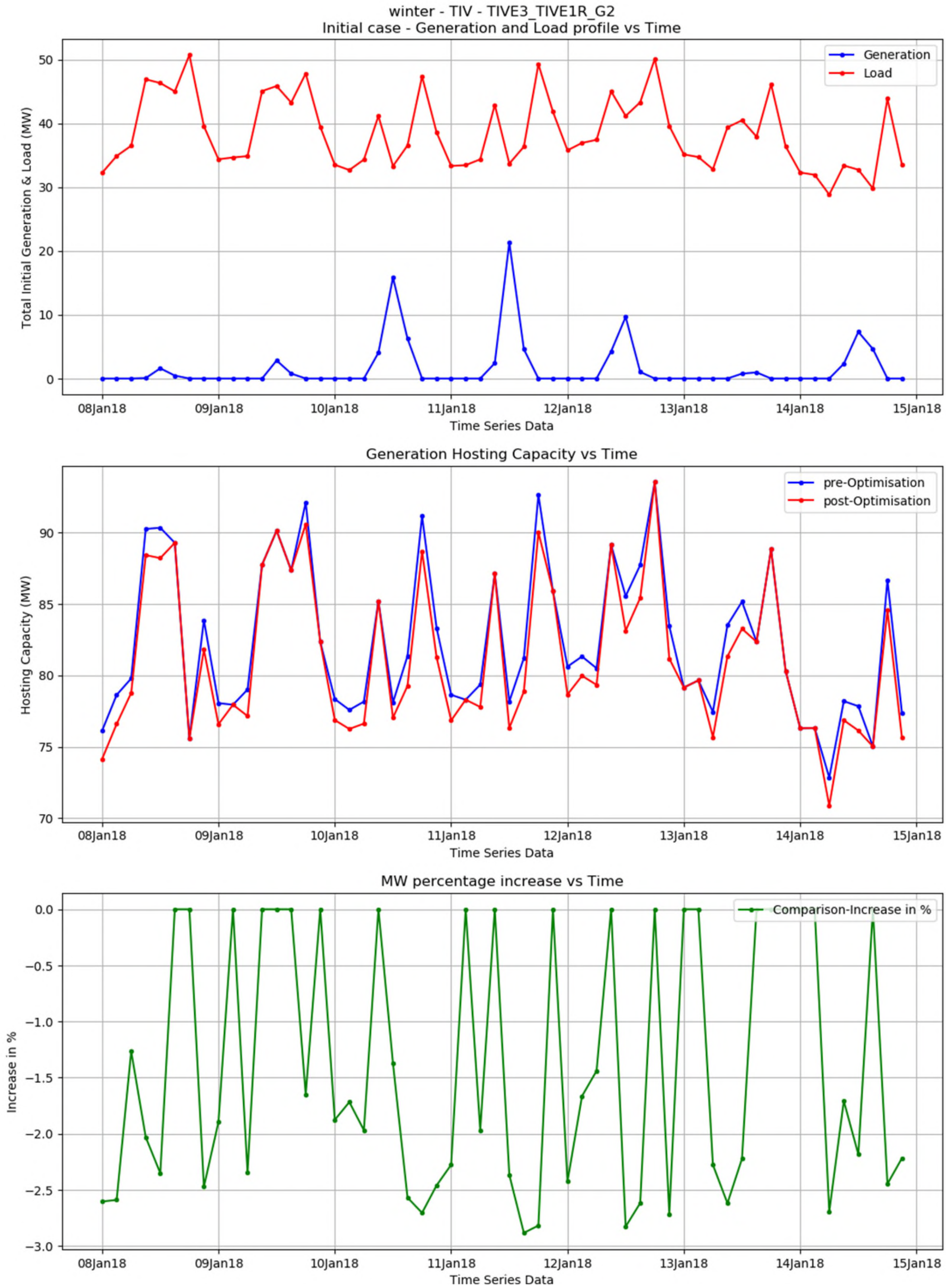
D.1.6. Worst contingency TIVE3_TIVE1R_G2 Summer Week



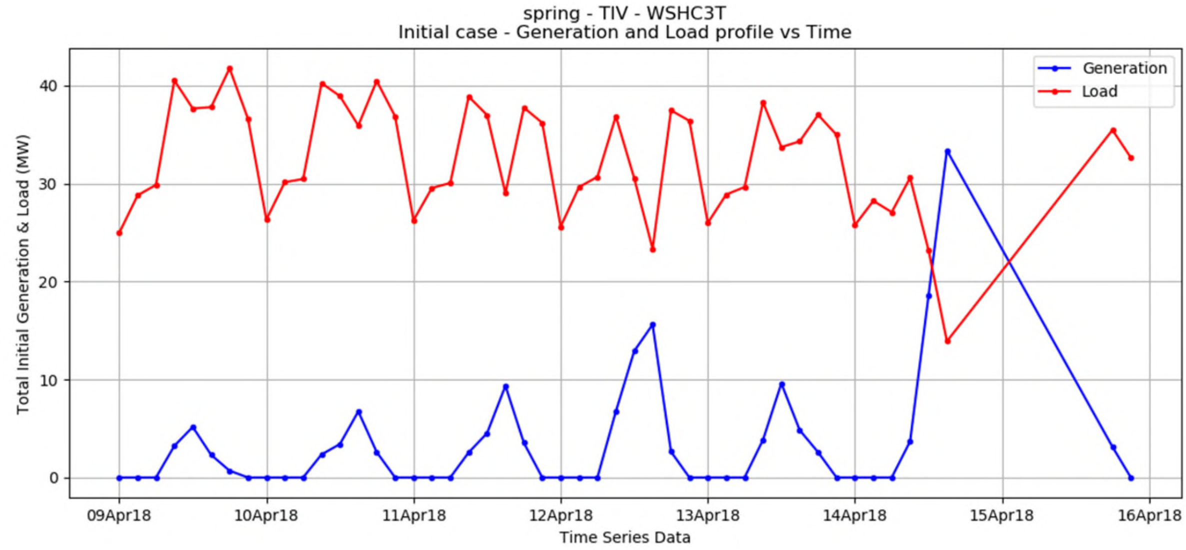
D.1.7. Worst contingency TIVE3_TIVE1R_G2 Autumn Week

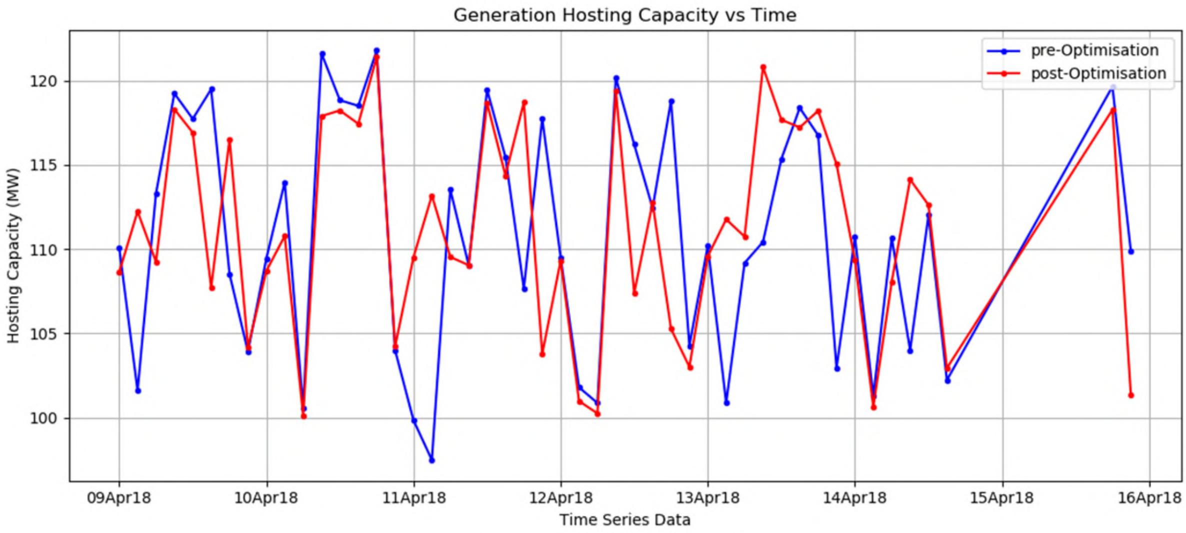


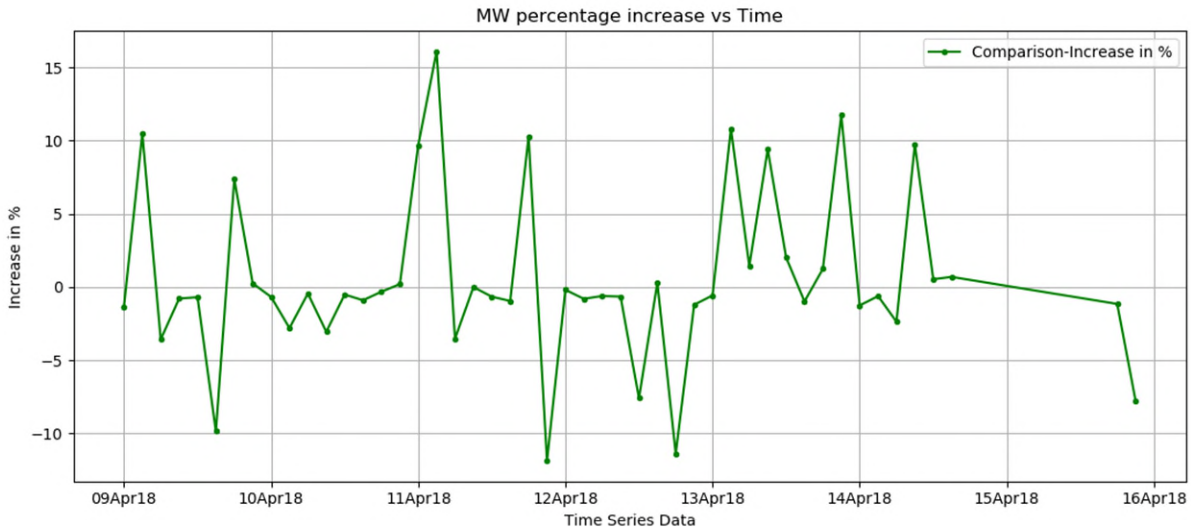
D.1.8. Worst contingency TIVE3_TIVE1R_G2 Winter Week



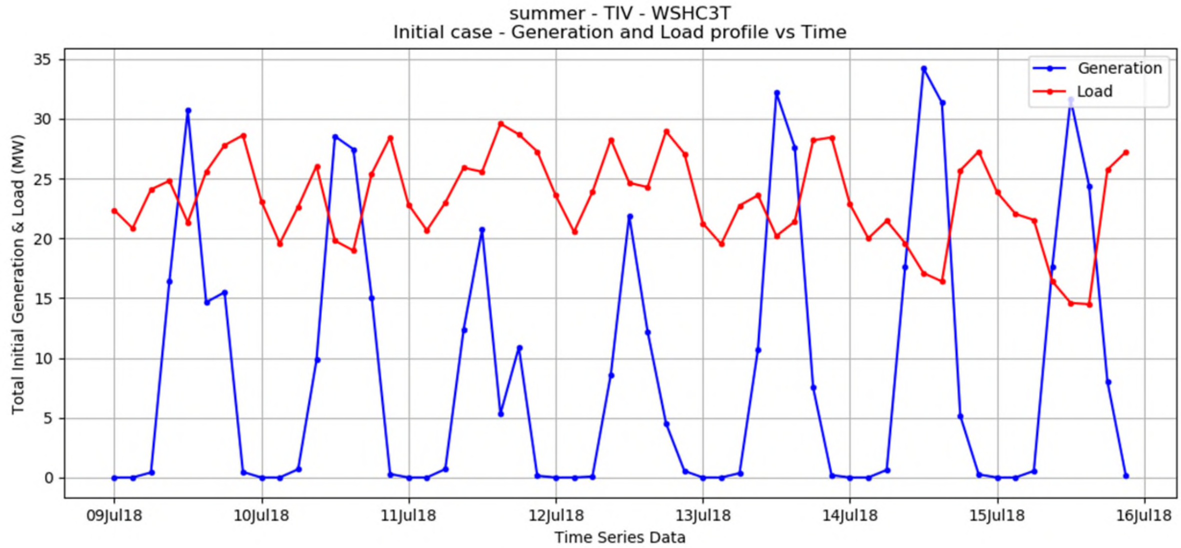
D.1.9. Best Contingency TIVM3J_WSHC3T_L1+WSHB3_WSHC3T_L1 Spring Week

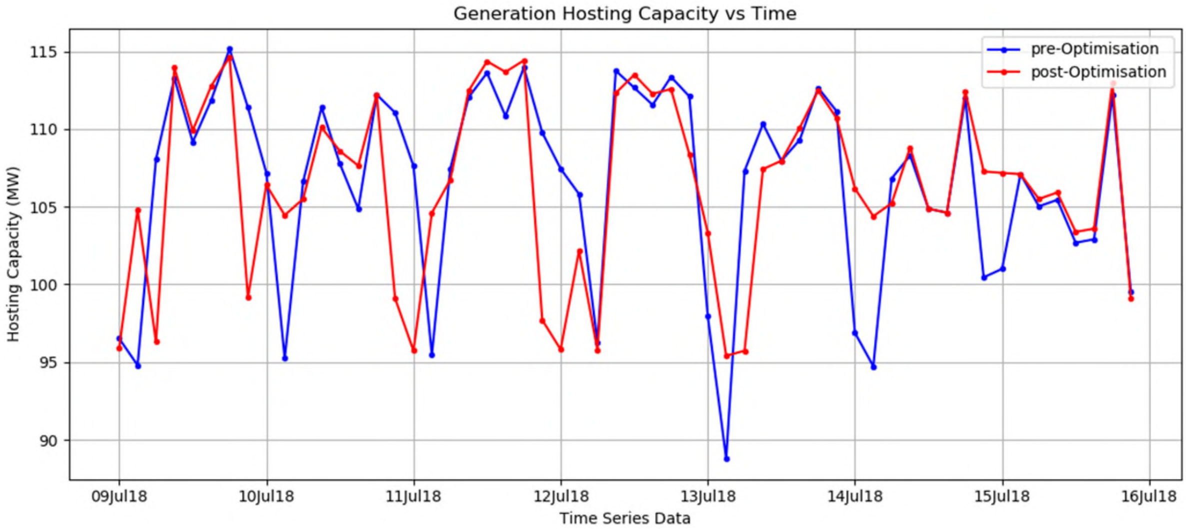


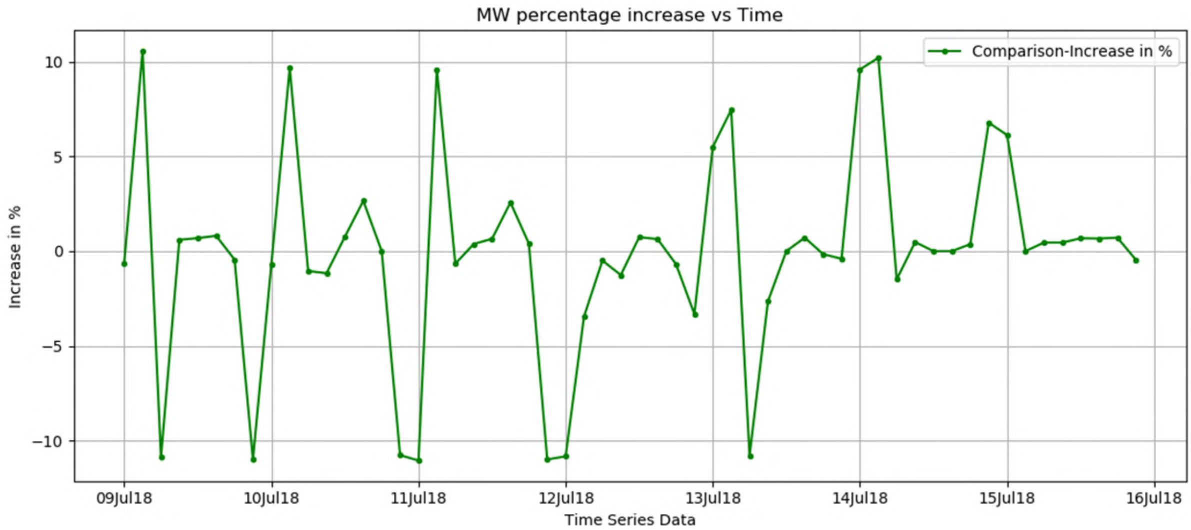




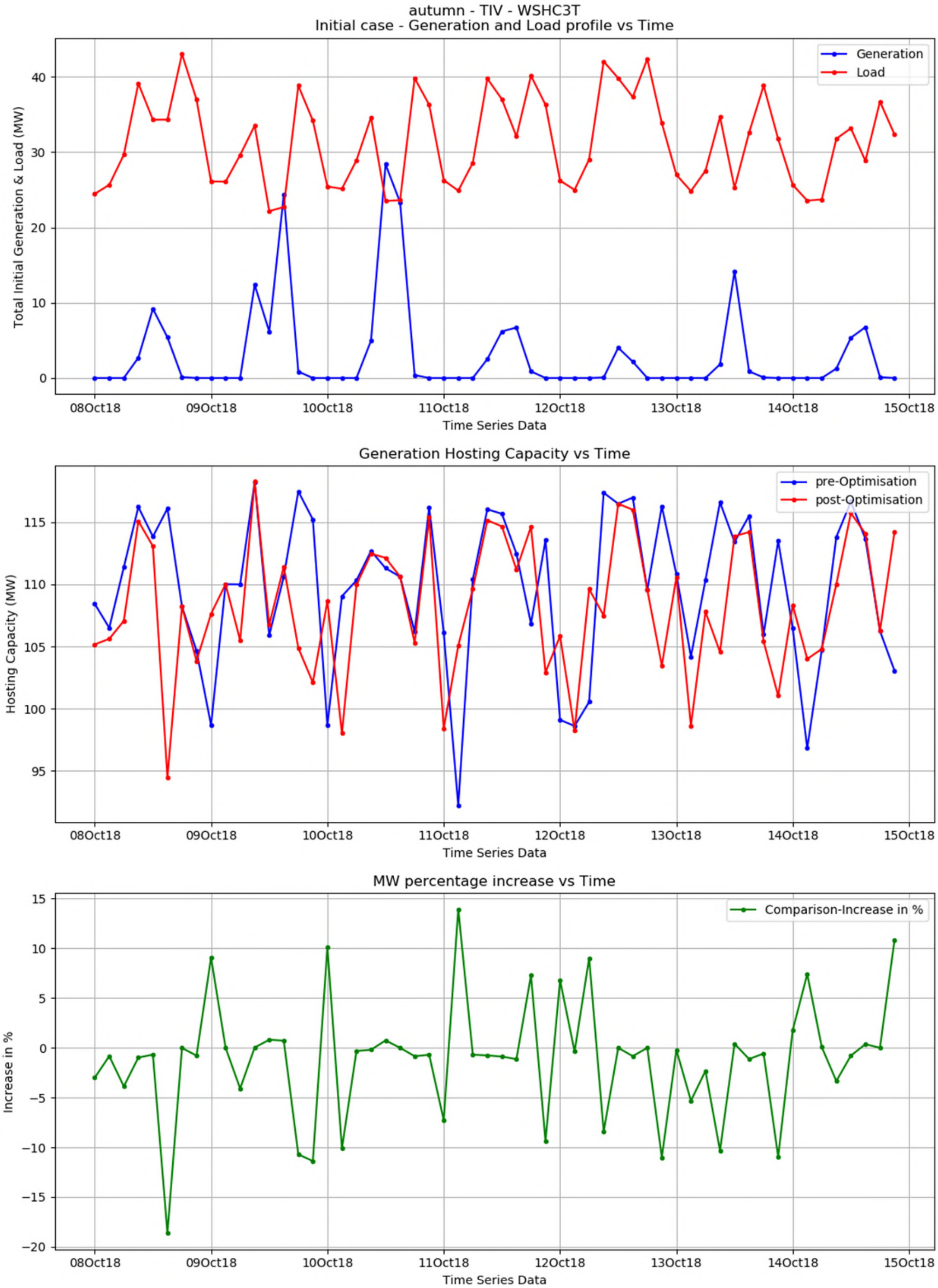
D.1.10. Best contingency TIVM3J_WSHC3T_L1+WSHB3_WSHC3T_L1 Summer Week



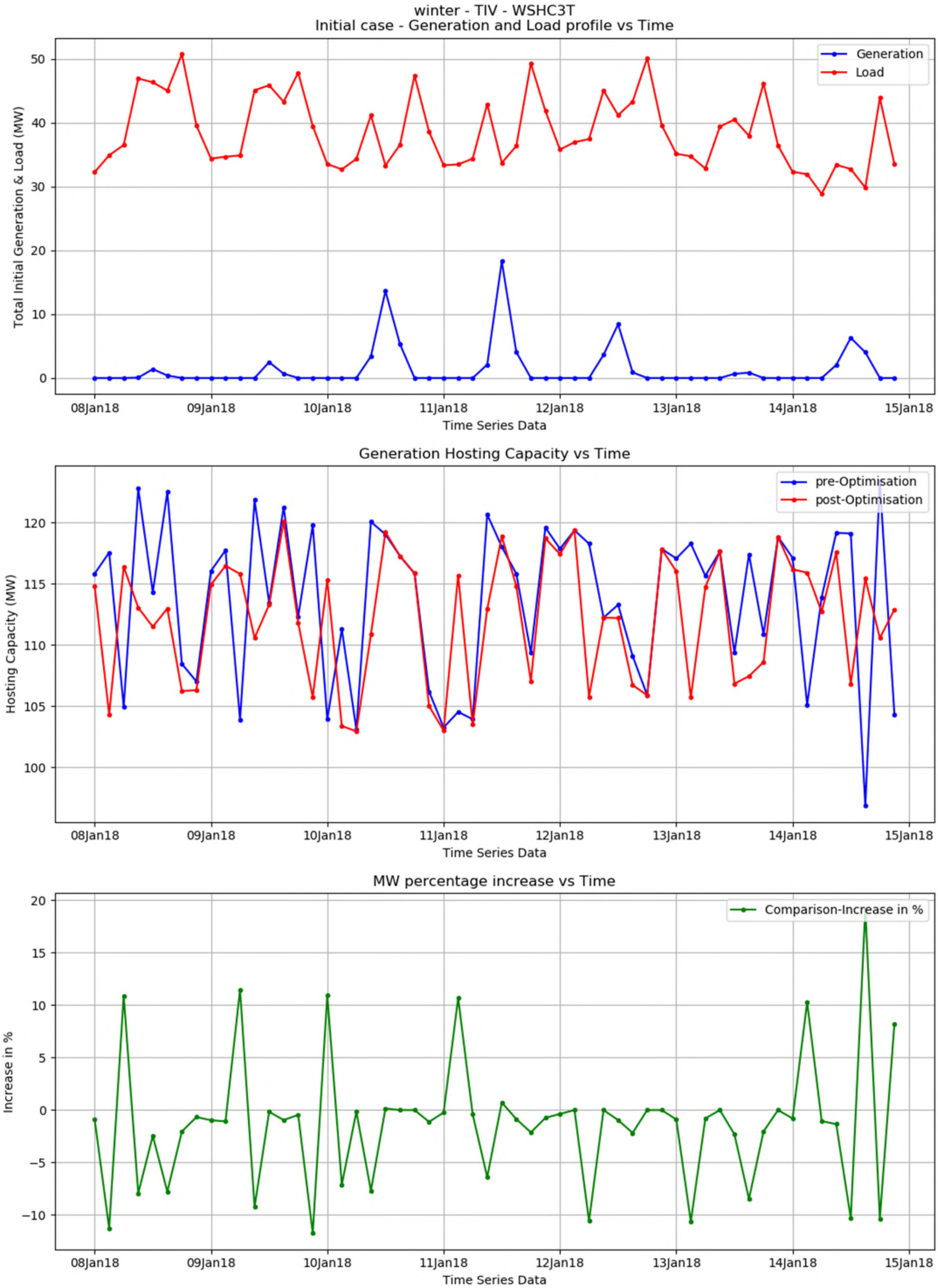




D.1.11. Best Contingency TIVM3J_WSHC3T_L1+WSHB3_WSHC3T_L1 Autumn Week

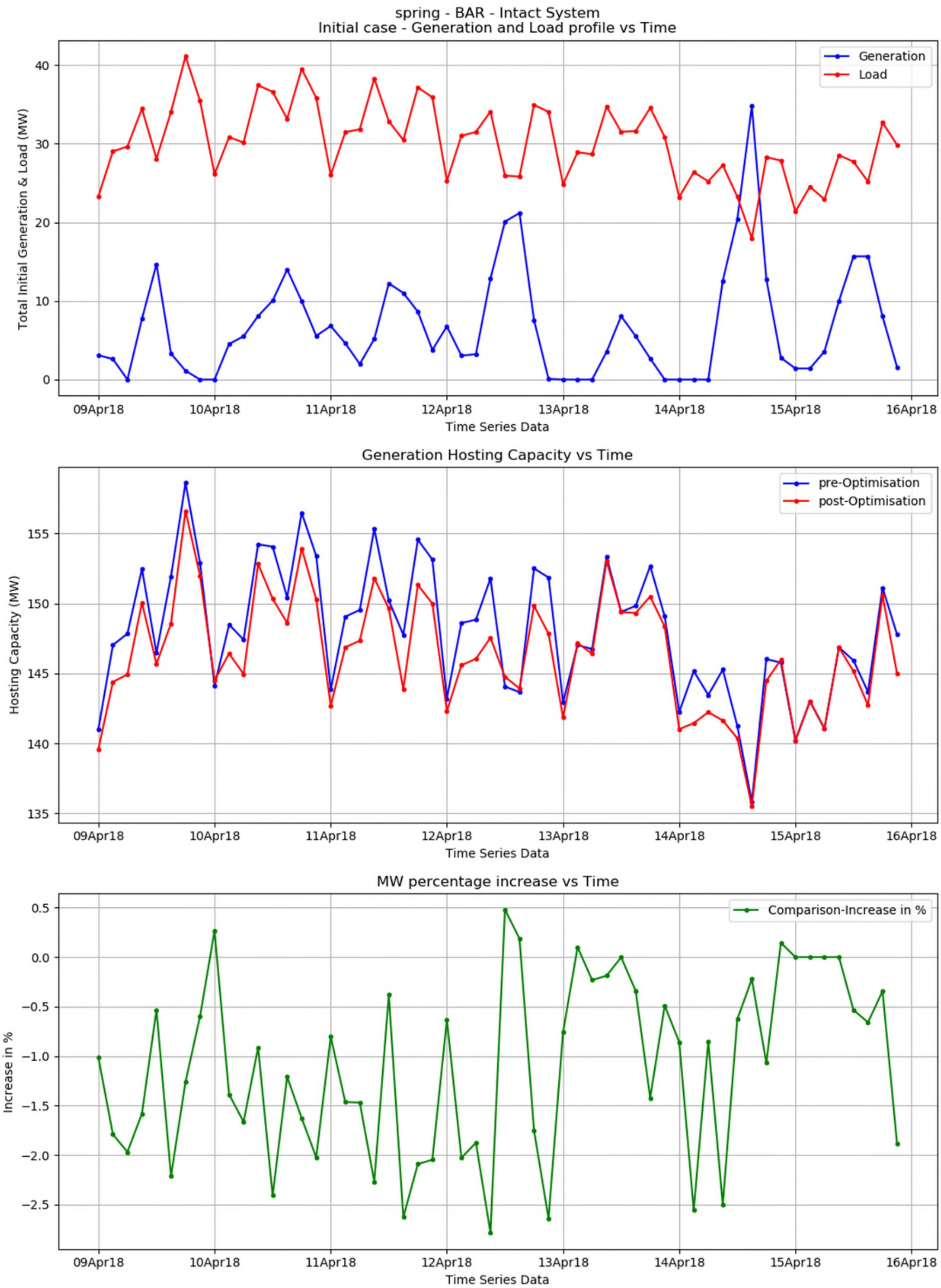


D.1.12. Best Contingency TIVM3J_WSHC3T_L1+WSHB3_WSHC3T_L1 Winter Week

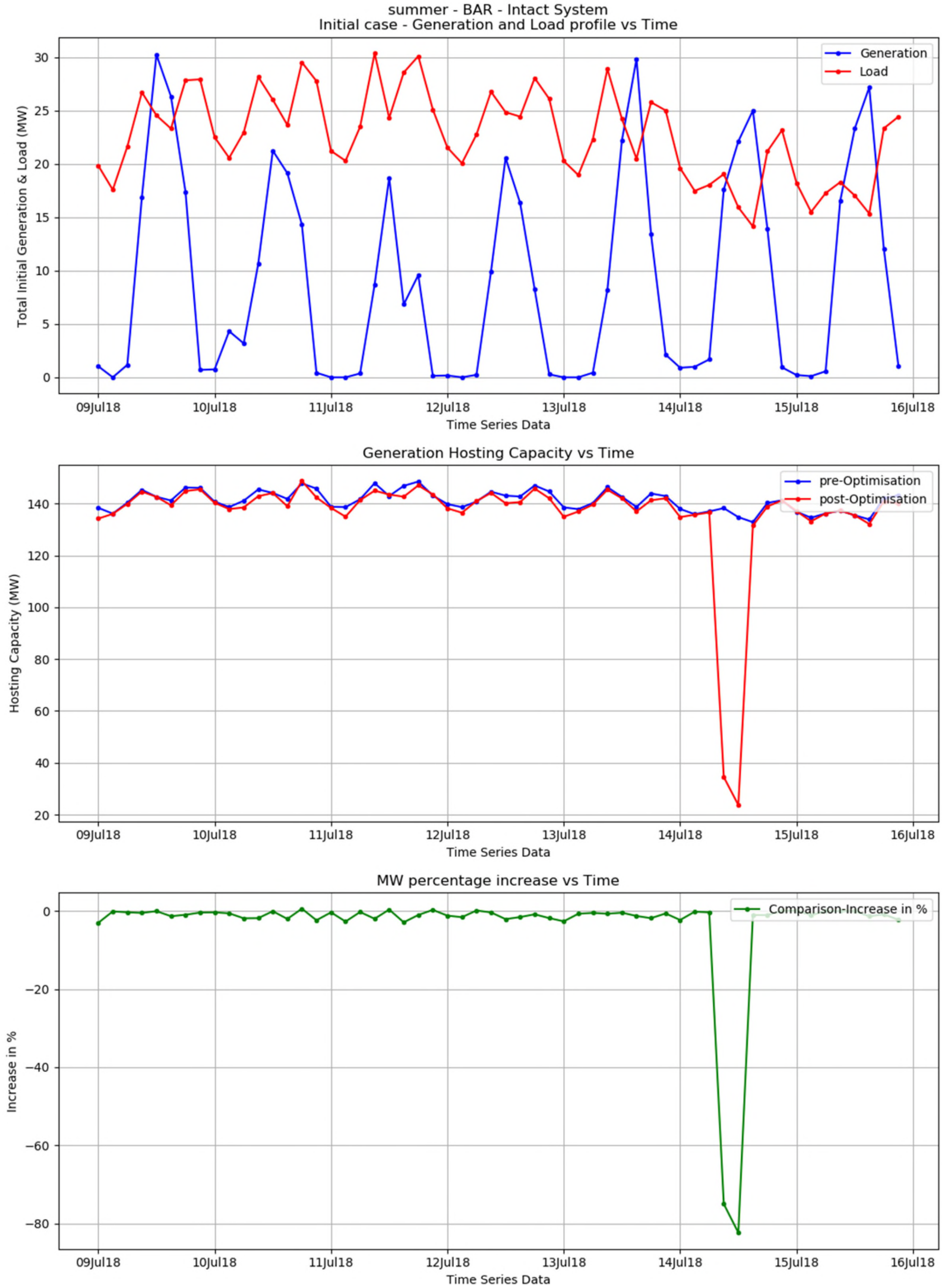


D.2. Barnstaple 33 kV BSP

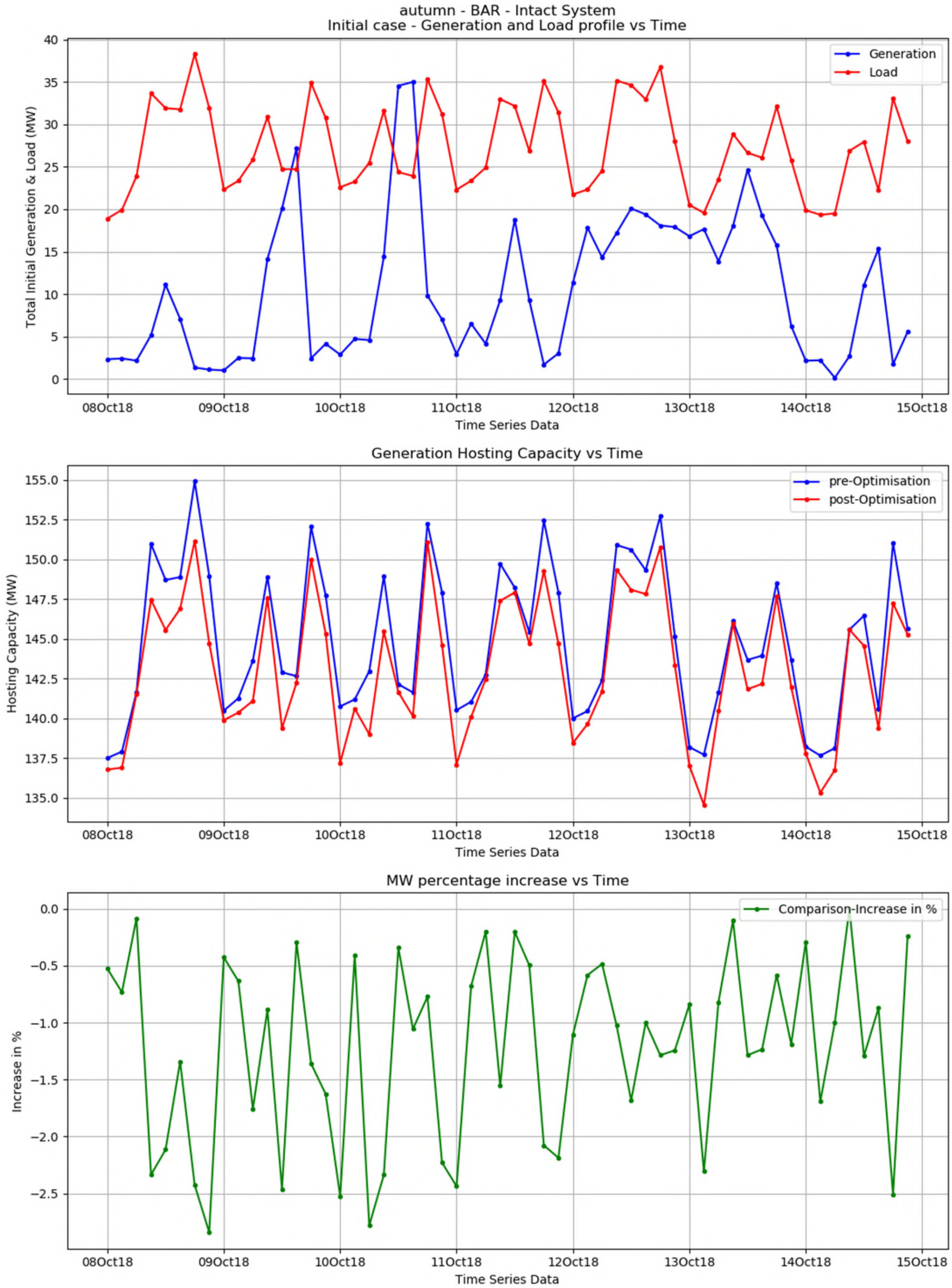
D.2.1. Intact System Spring Week



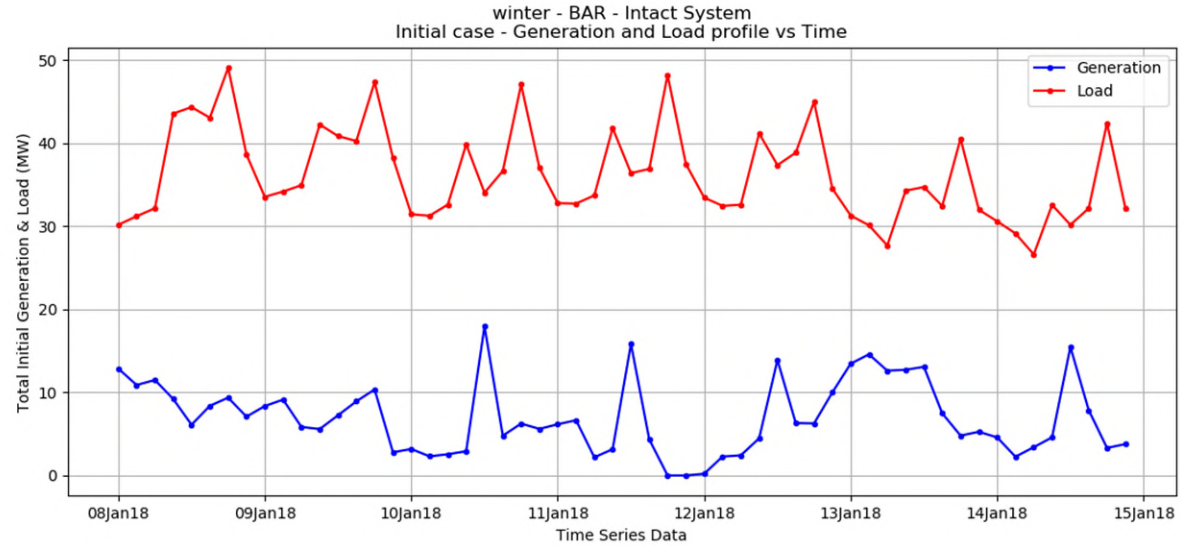
D.2.2. Intact System Summer Week

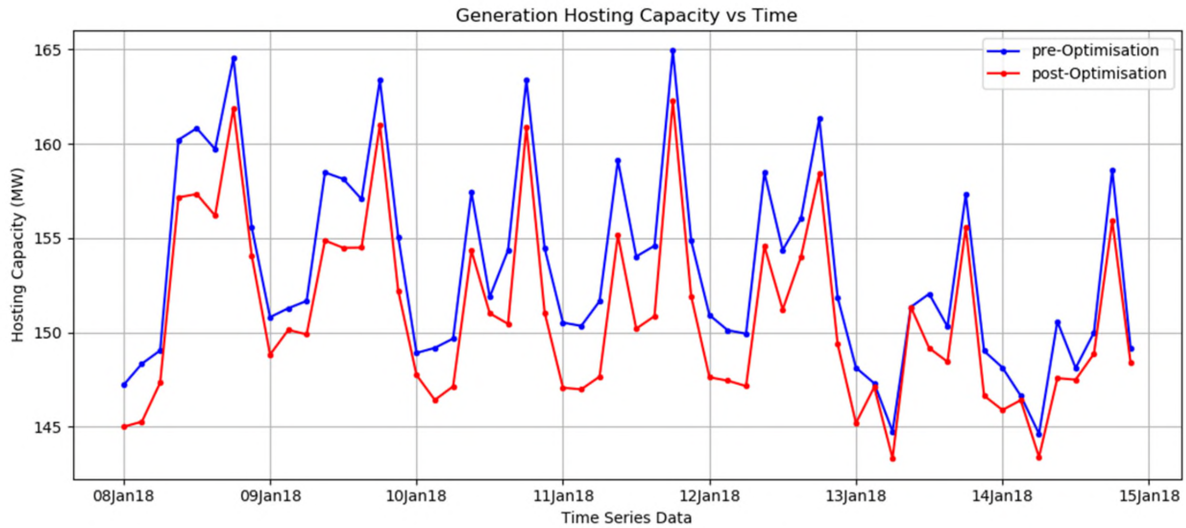


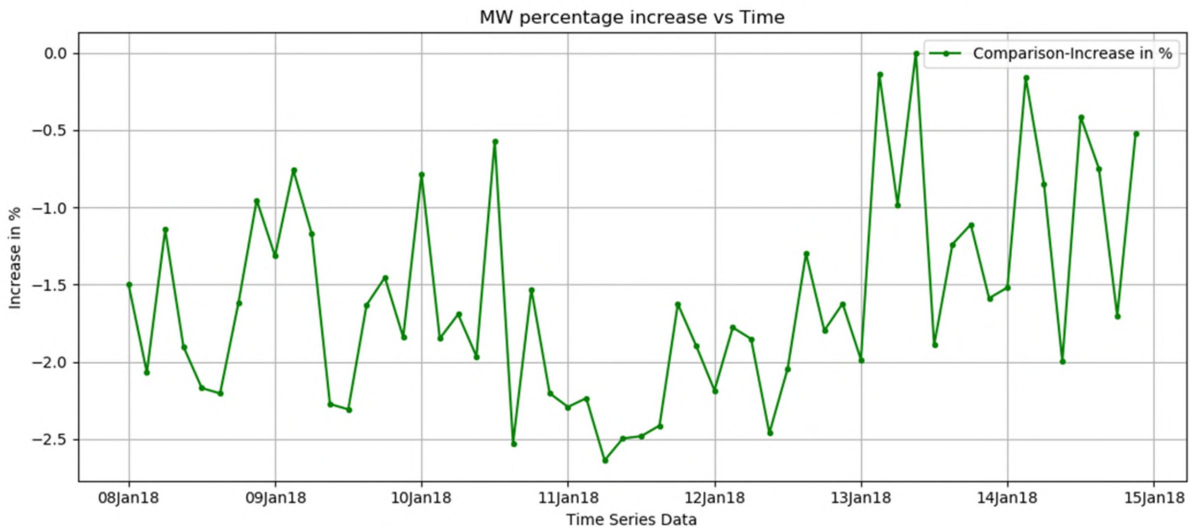
D.2.3. Intact System Autumn Week



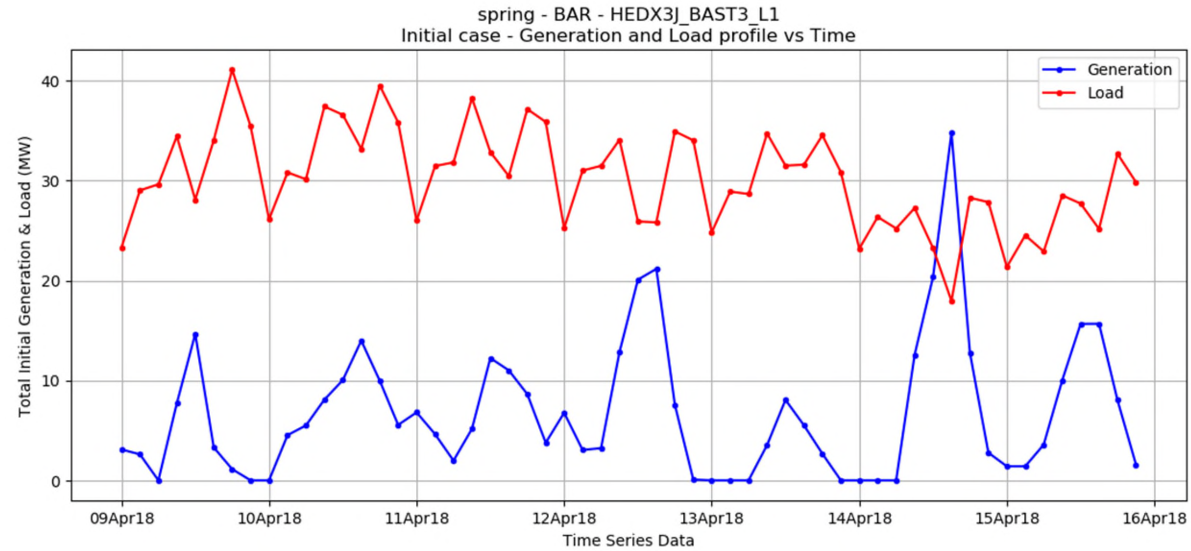
D.2.4. Intact System Winter Week

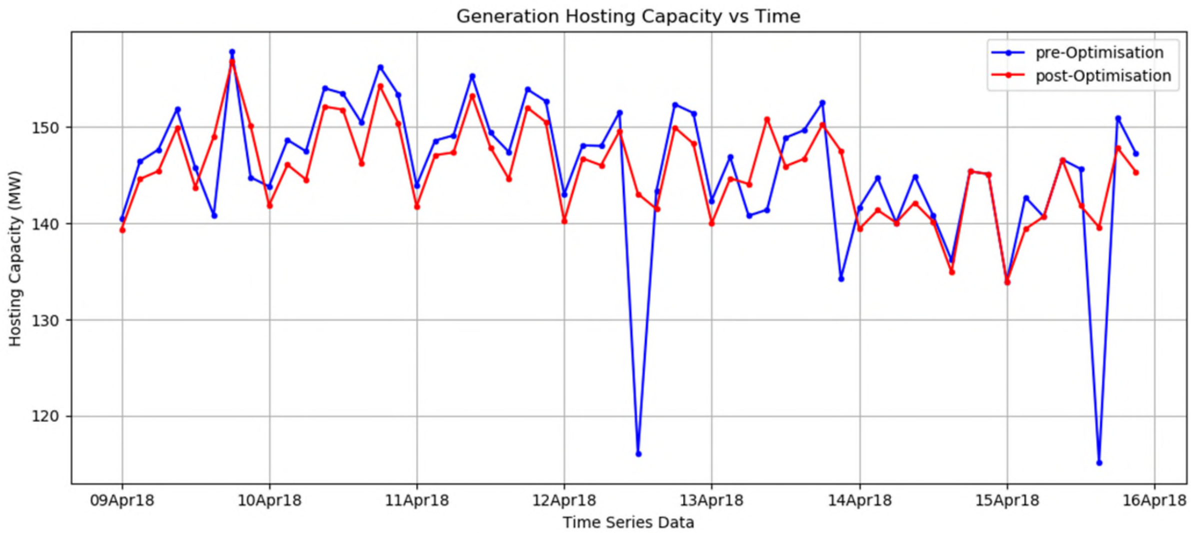


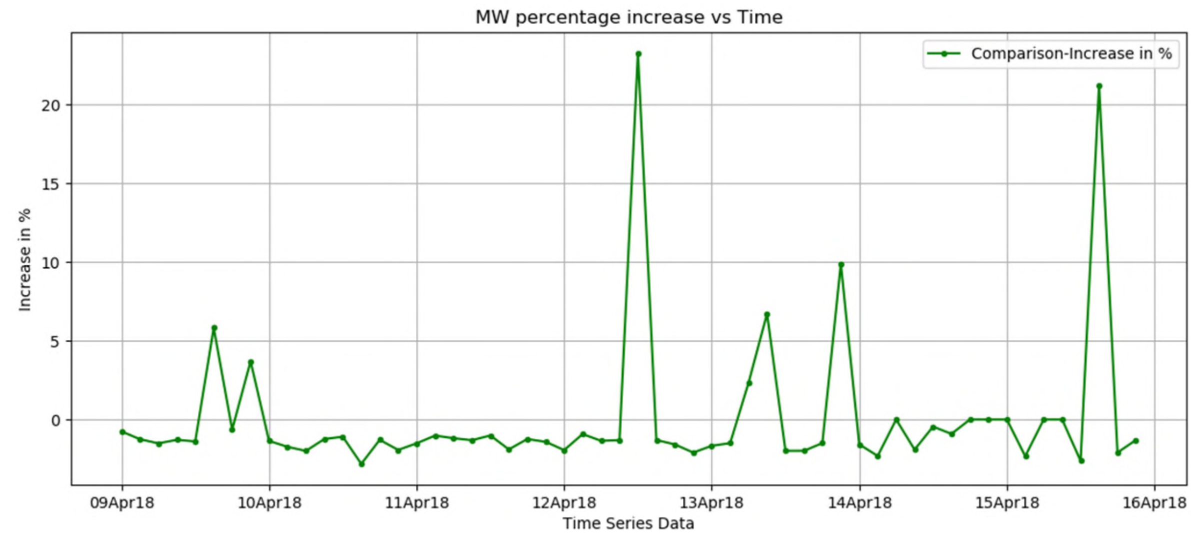




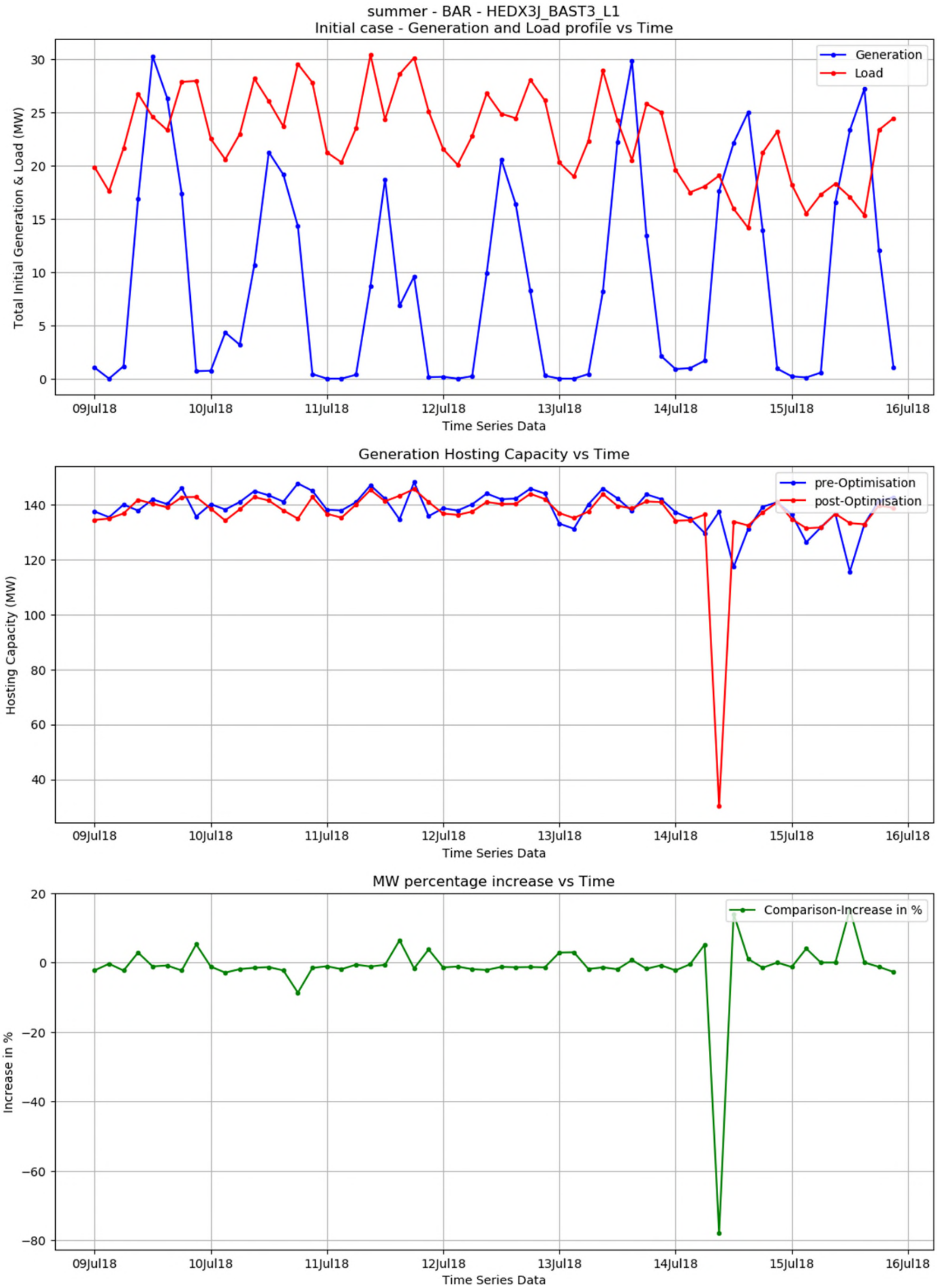
D.2.5. Worst Contingency HEDX3J_BAST3_L1 Spring Week



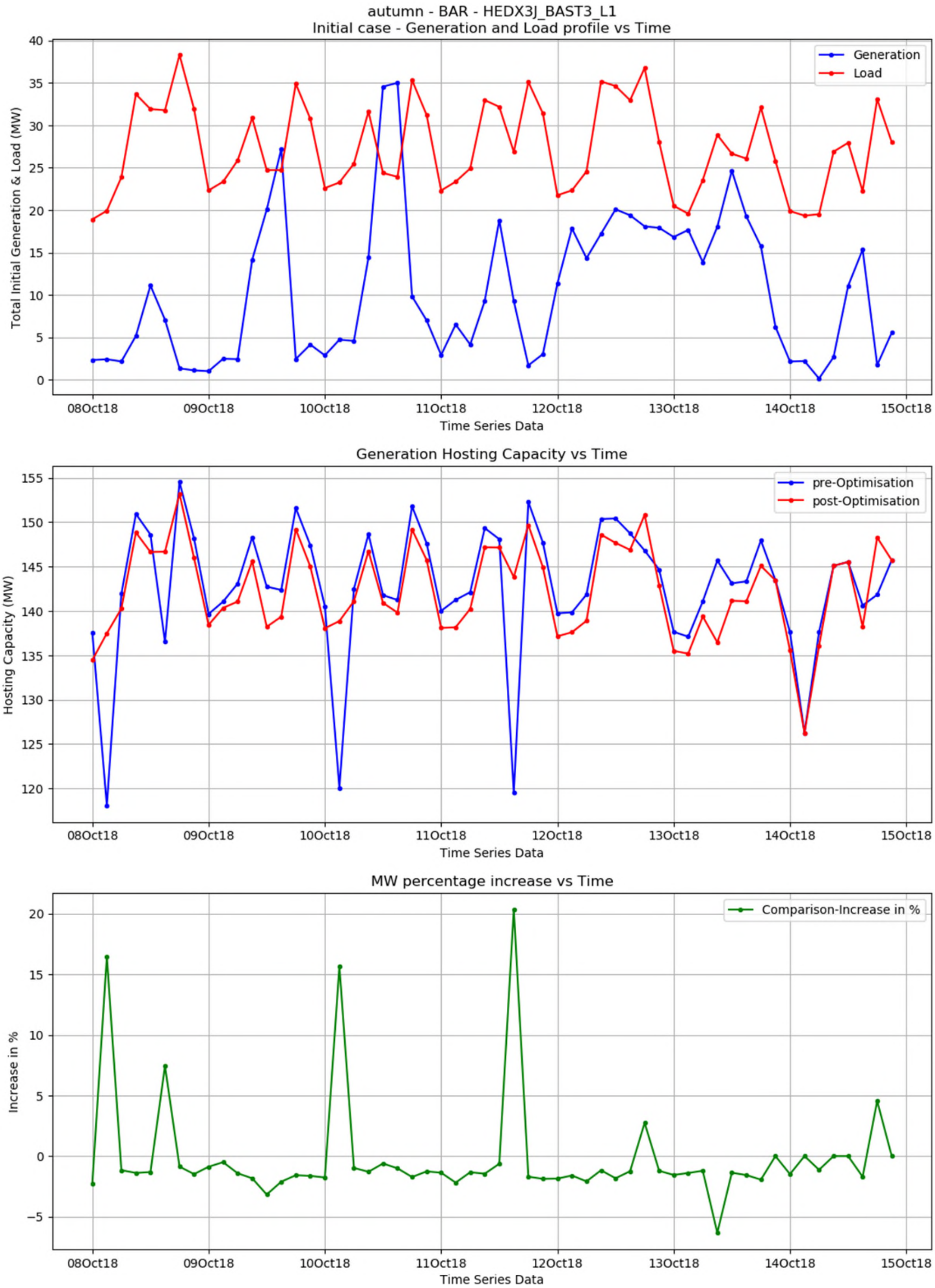




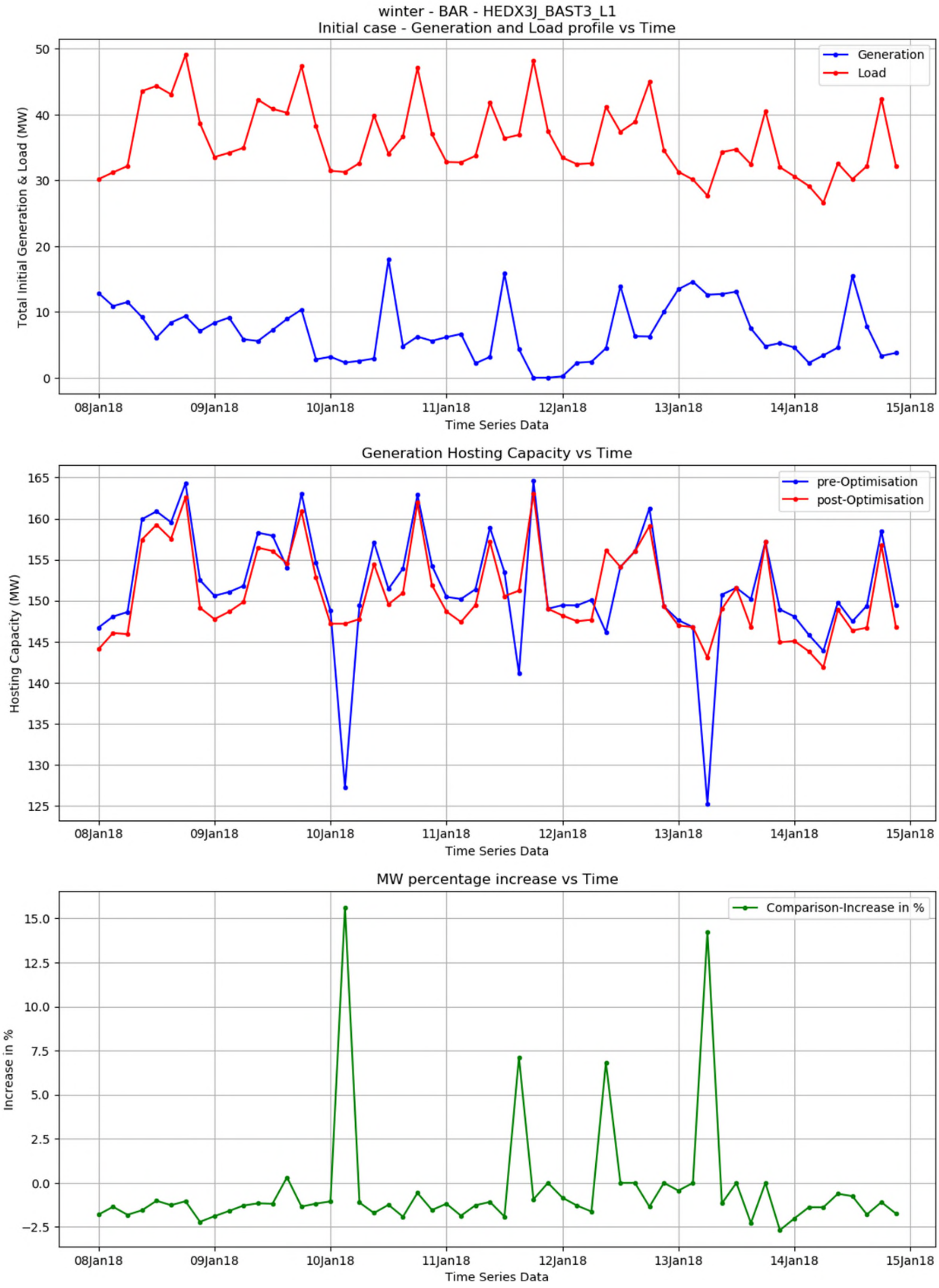
D.2.6. Worst Contingency HEDX3J_BAST3_L1 Summer Week



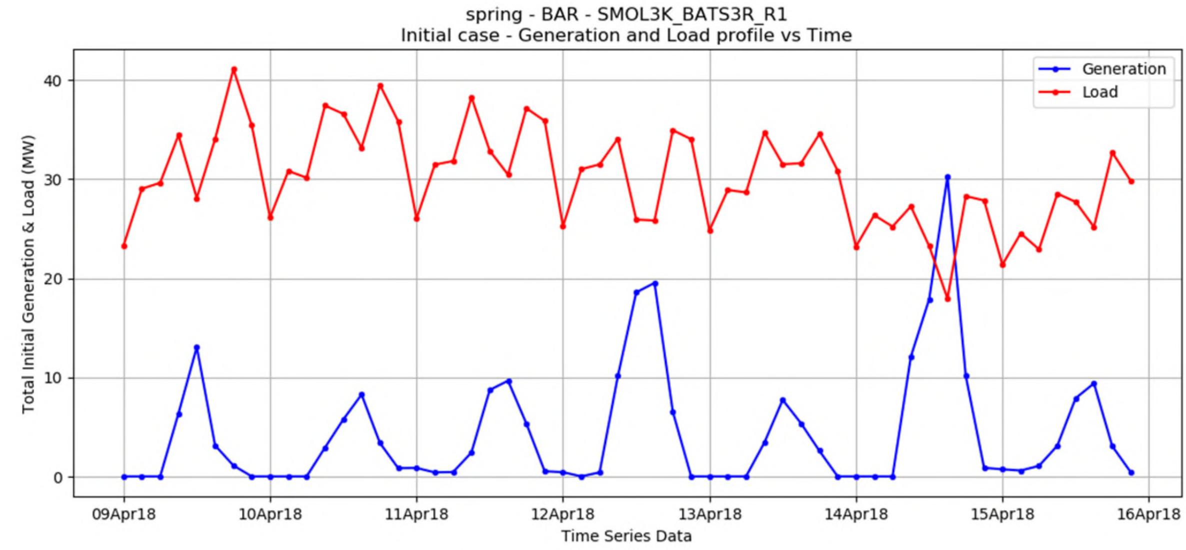
D.2.7. Worst Contingency HEDX3J_BAST3_L1 Autumn Week

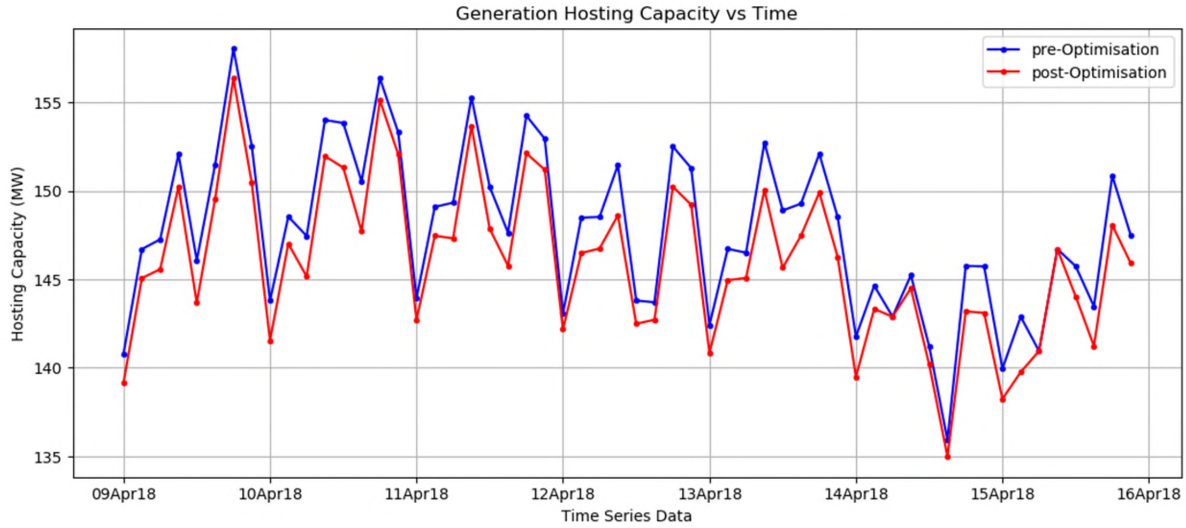


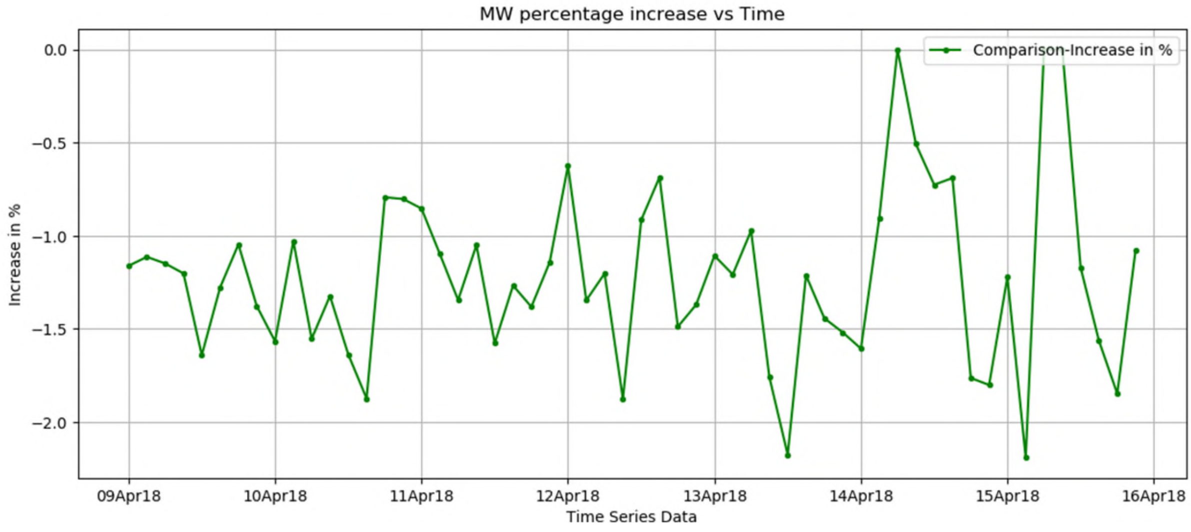
D.2.8. Worst Contingency HEDX3J_BAST3_L1 Winter Week



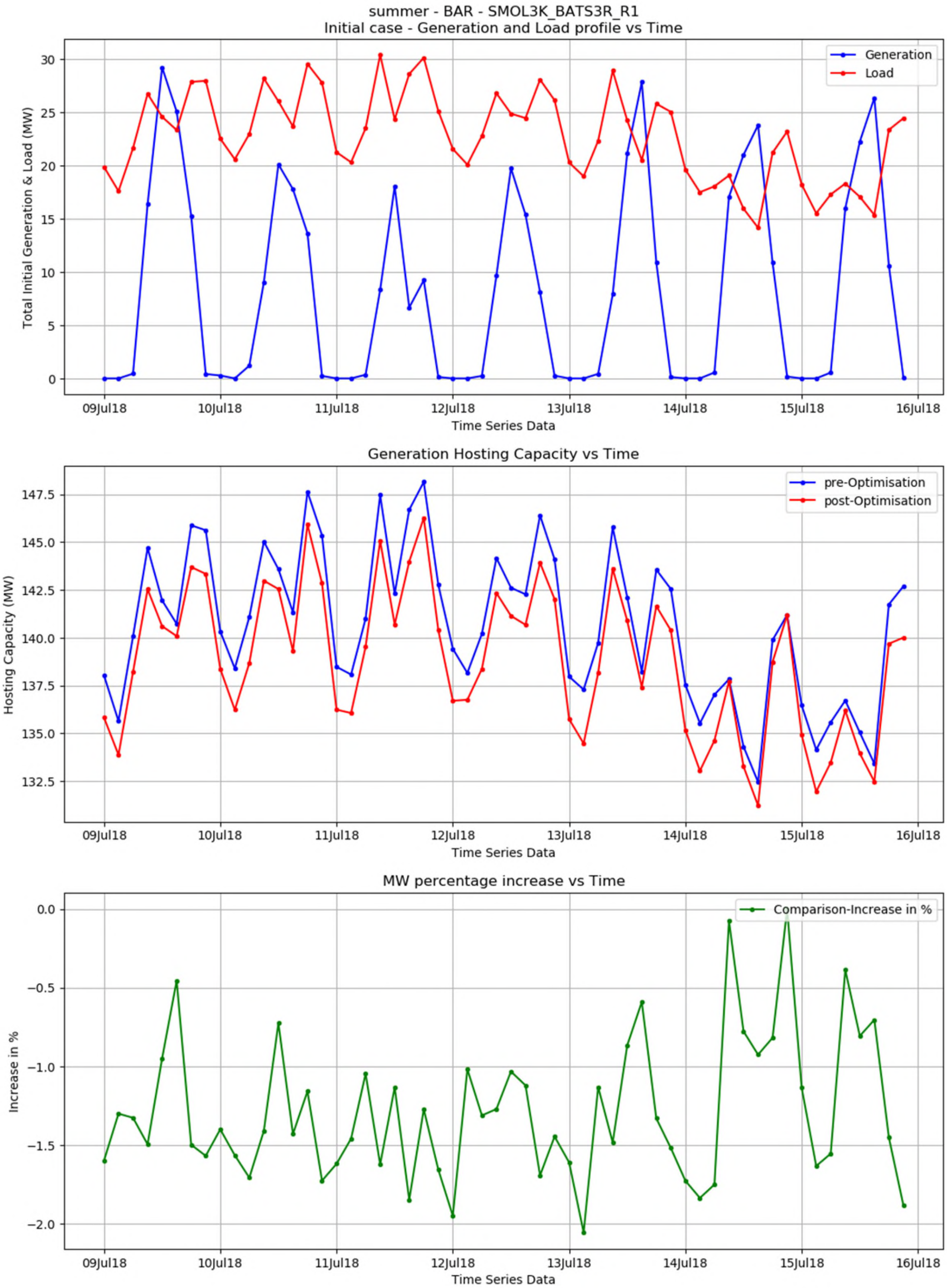
D.2.9. Best Contingency SMOL3K_BATS3R_R1 Spring Week



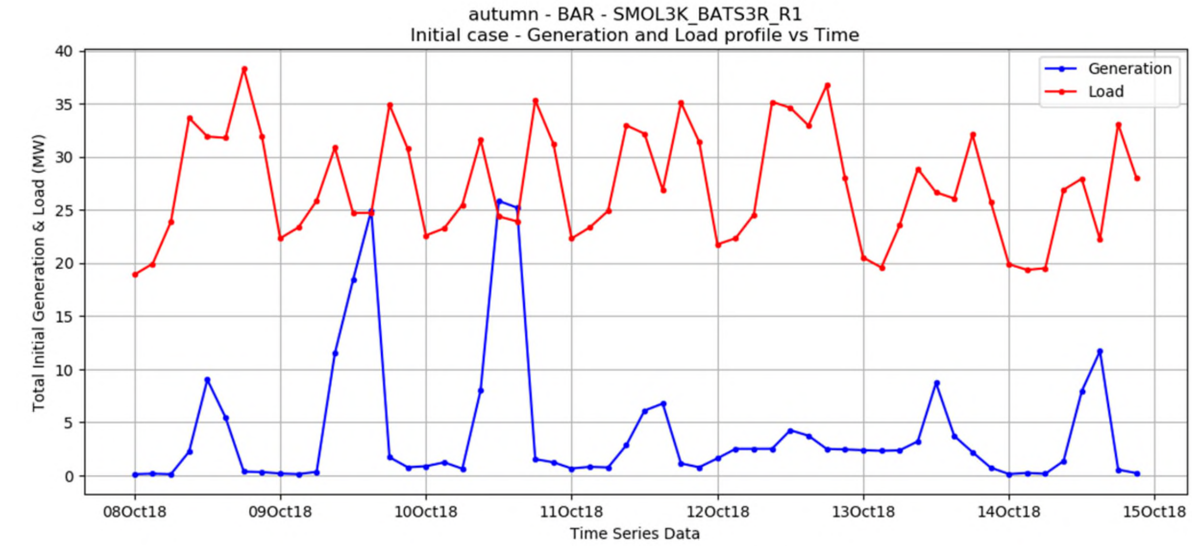


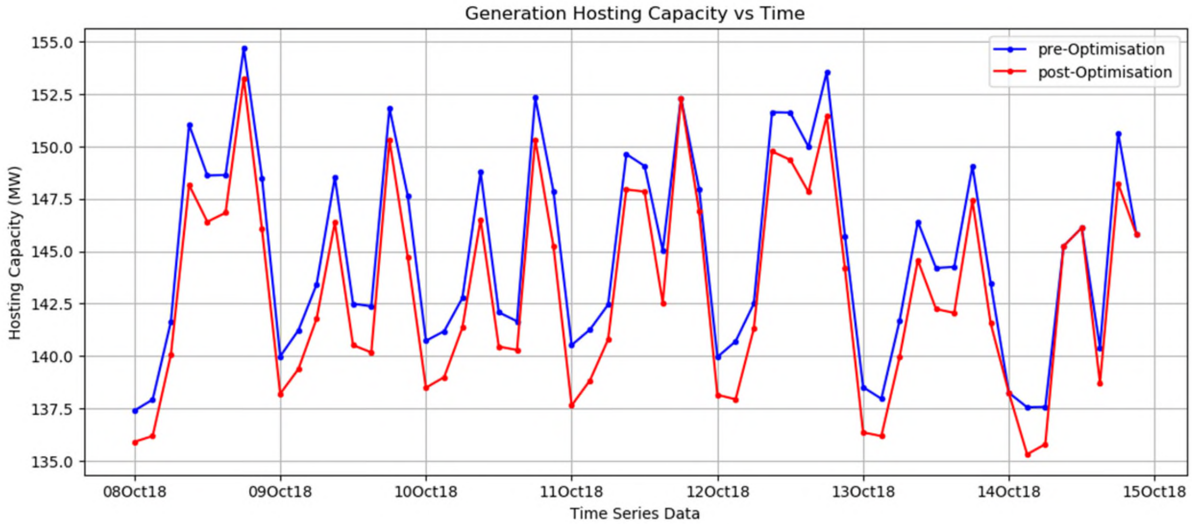


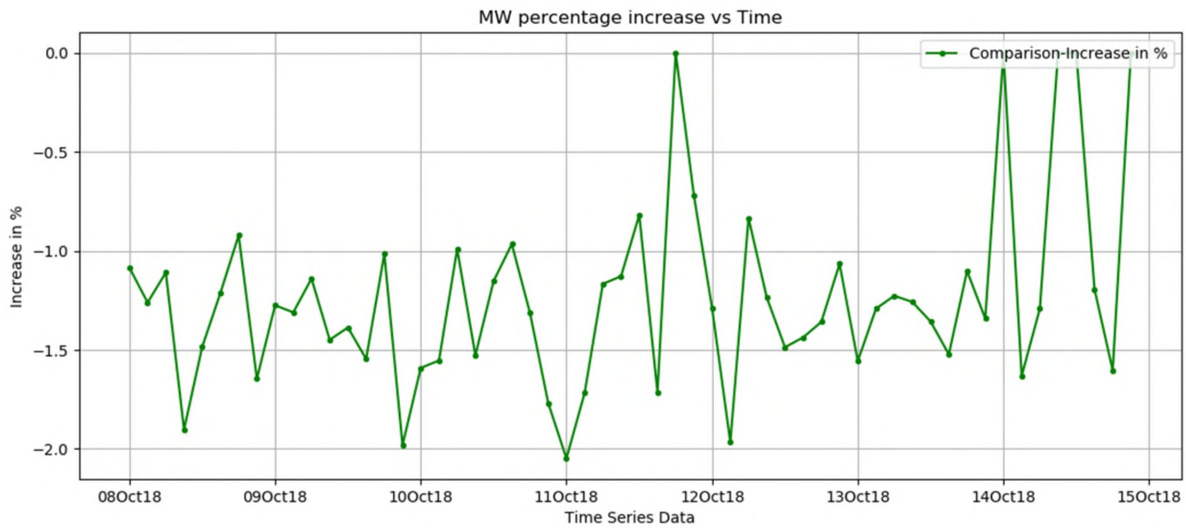
D.2.10. Best Contingency SMOL3K_BATS3R_R1 Summer Week



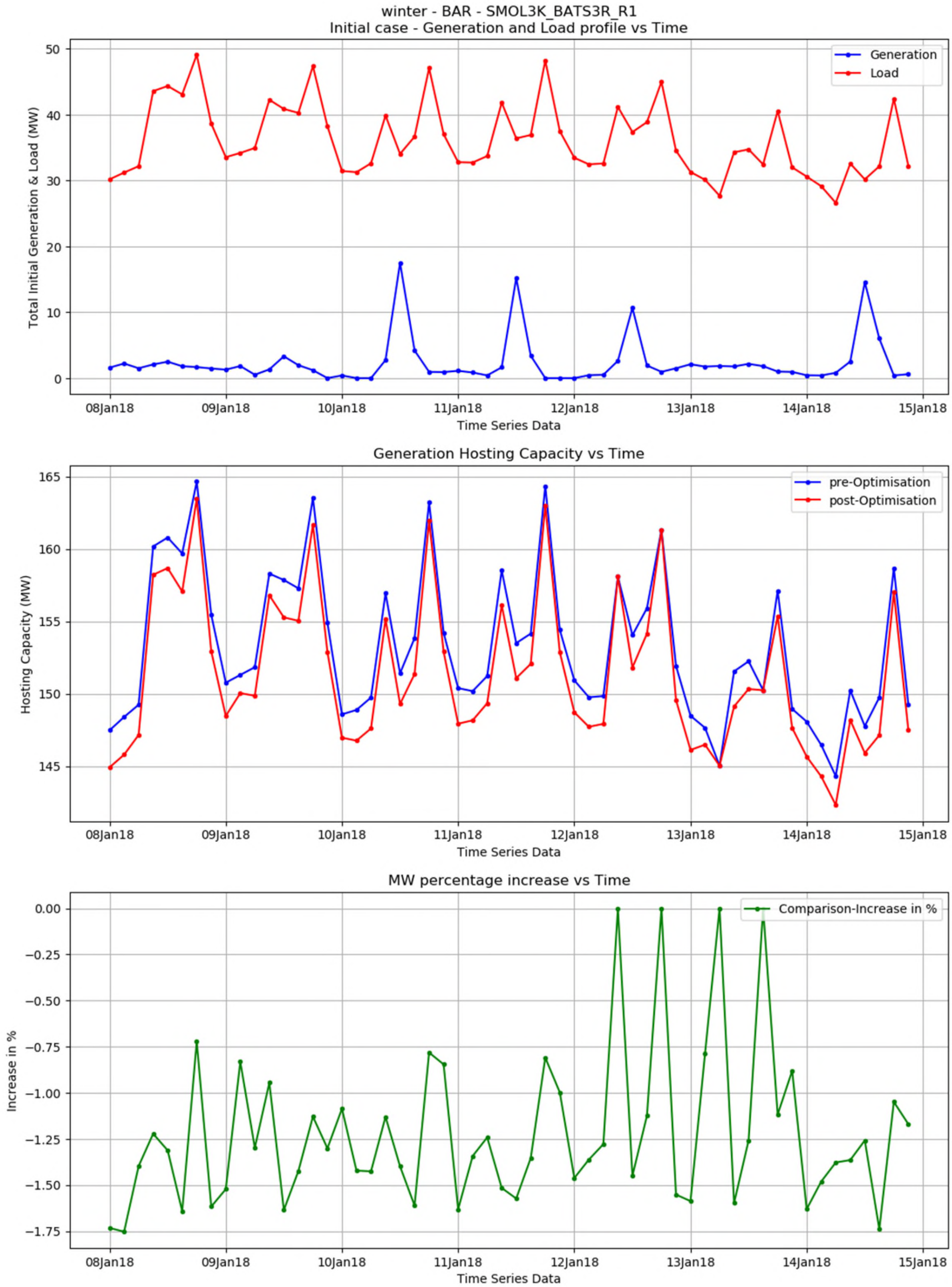
D.2.11. Best Contingency SMOL3K_BATS3R_R1 Autumn Week





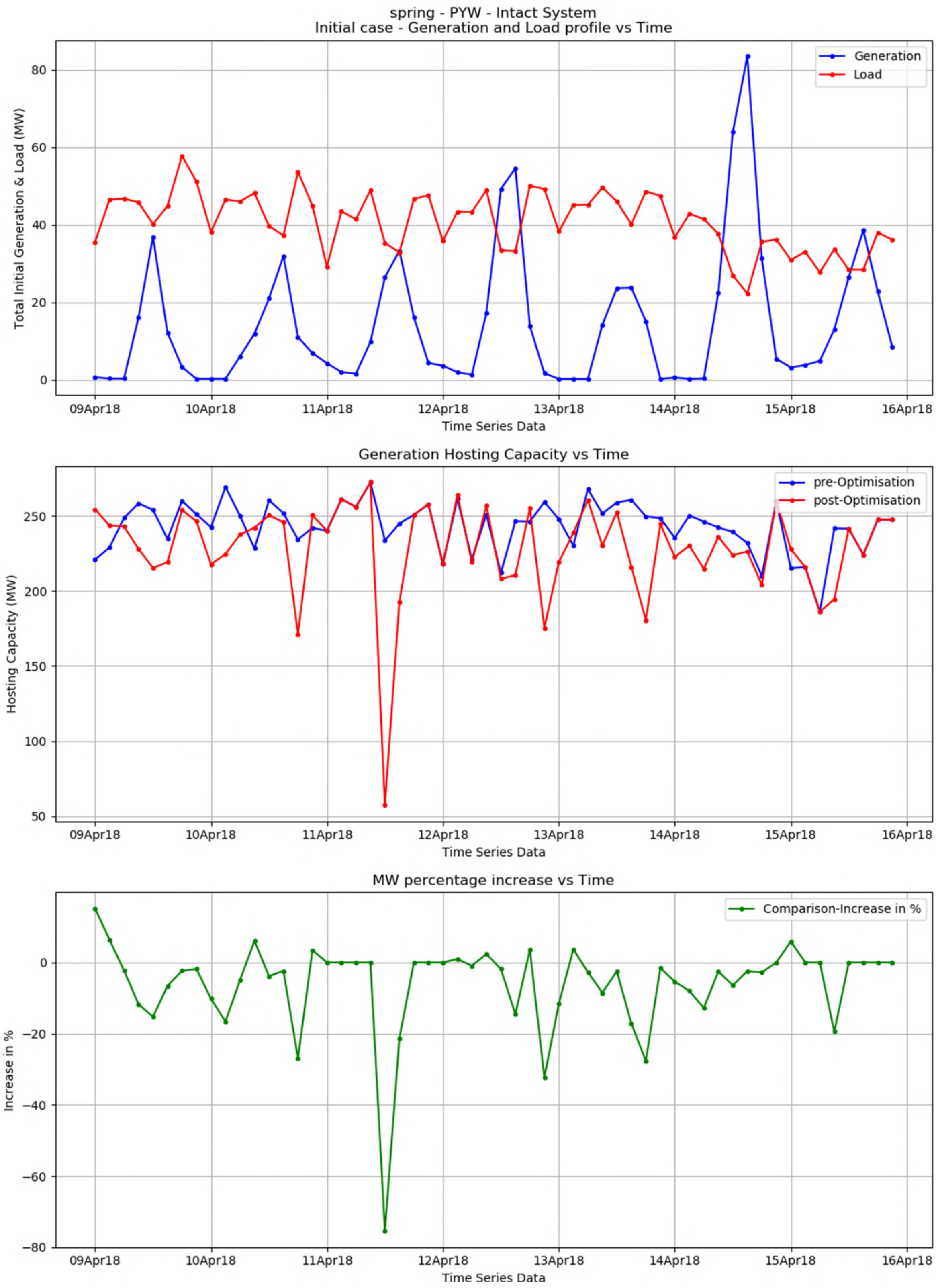


D.2.12. Best Contingency SMOL3K_BATS3R_R1 Winter Week

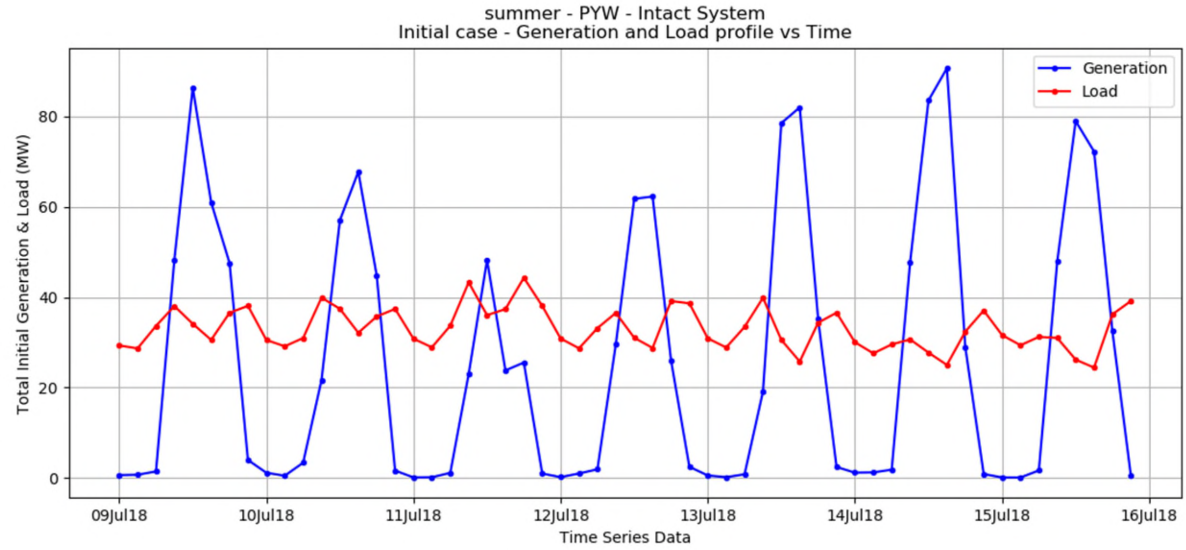


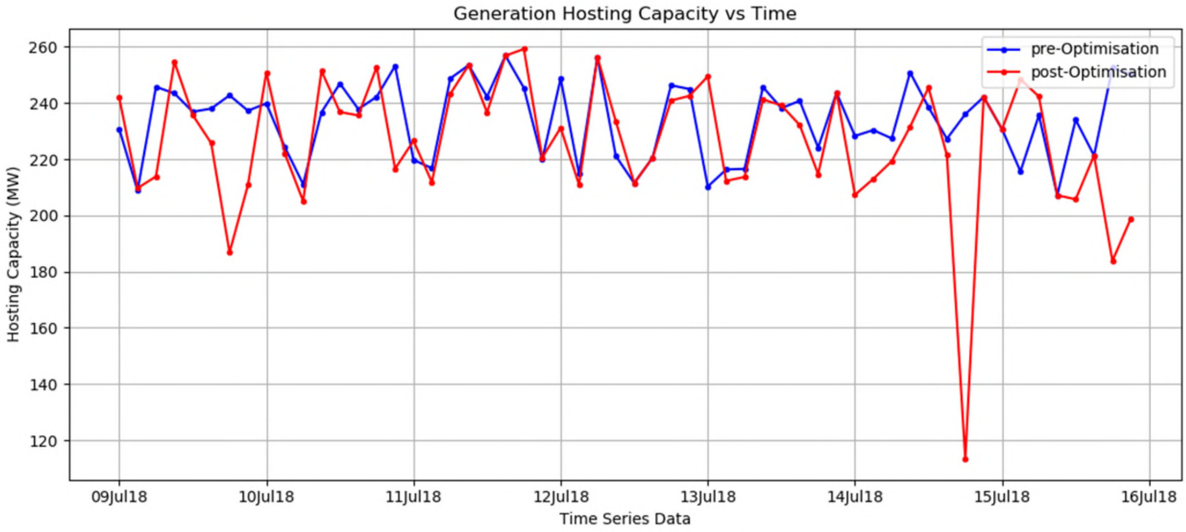
D.3. Pyworthy and North Tawton 33 kV BSPs

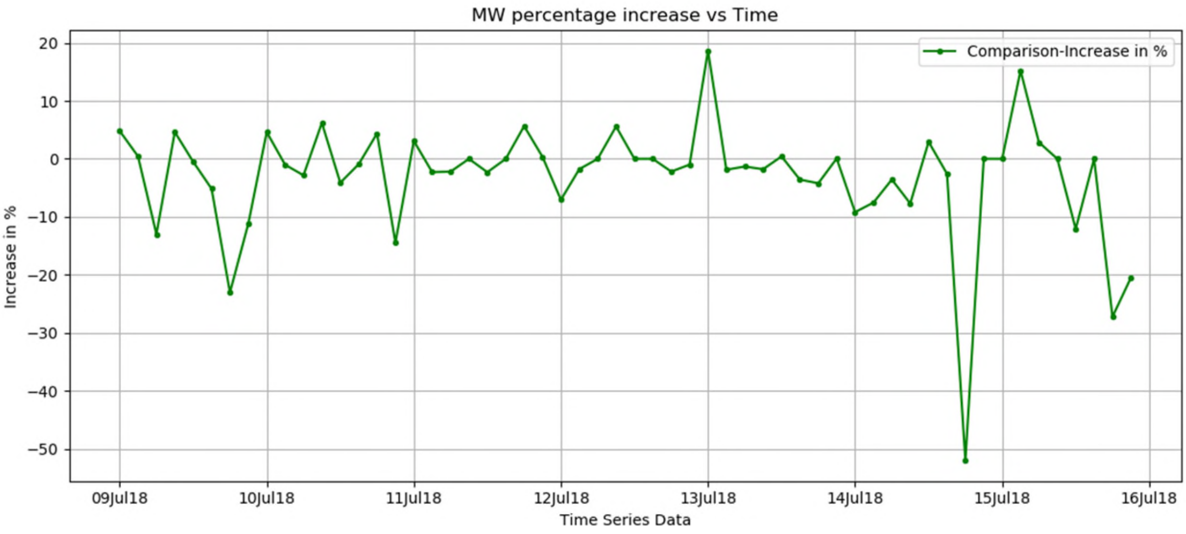
D.3.1. Intact System Spring Week



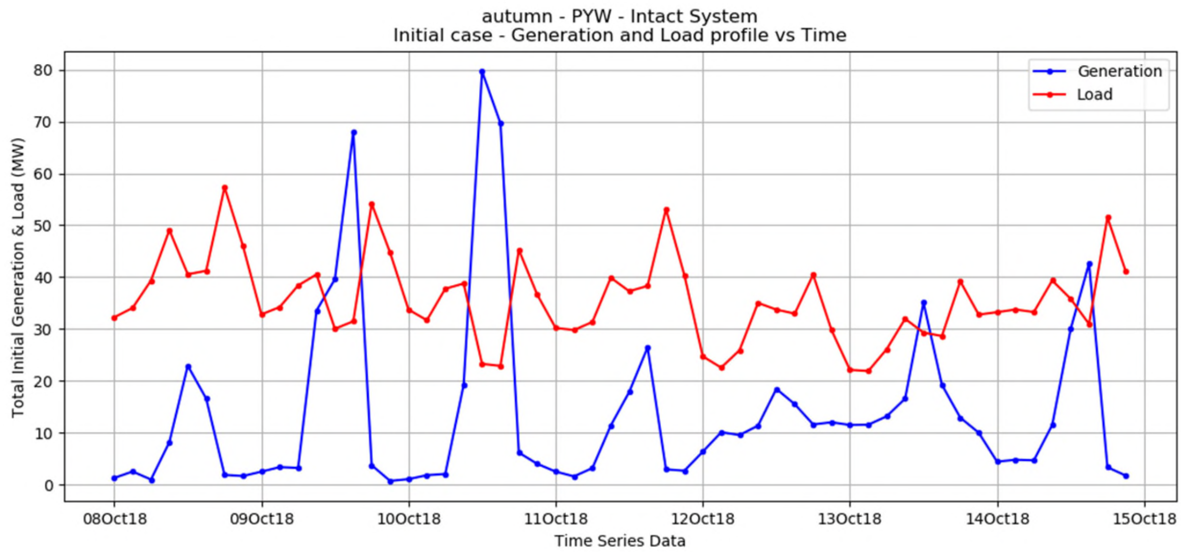
D.3.2. Intact System Summer Week

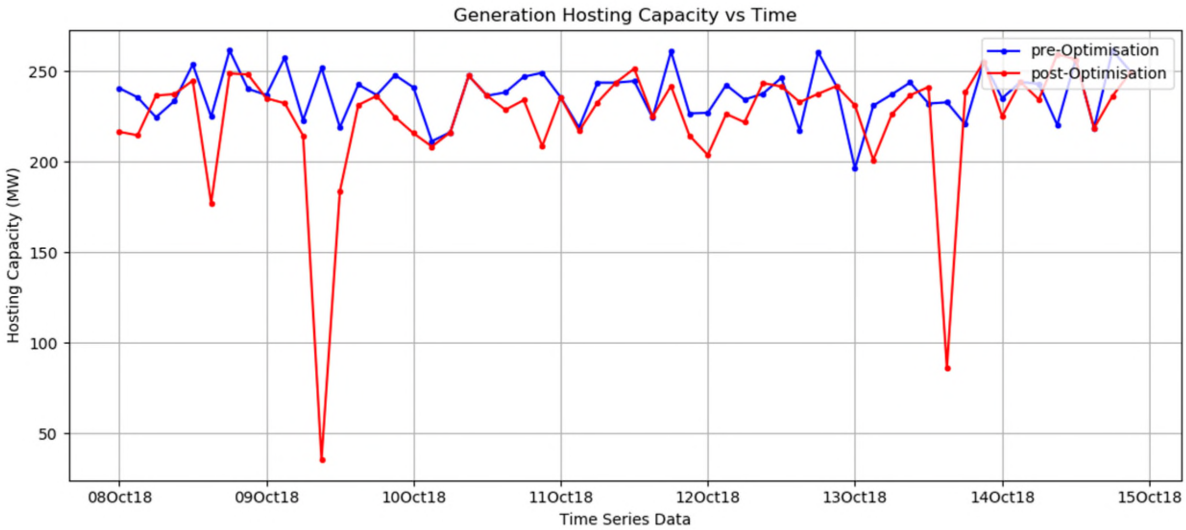


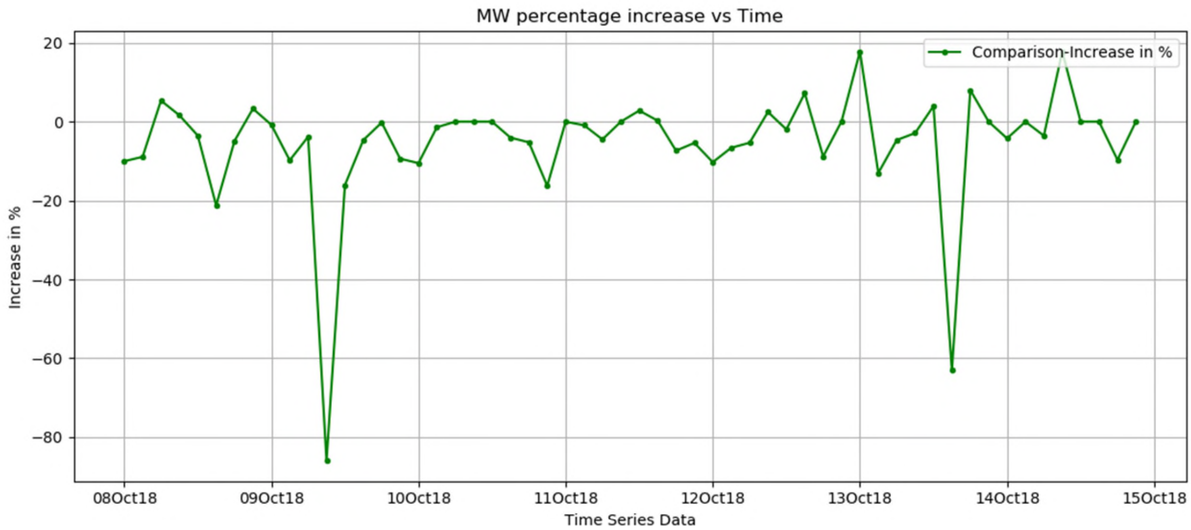




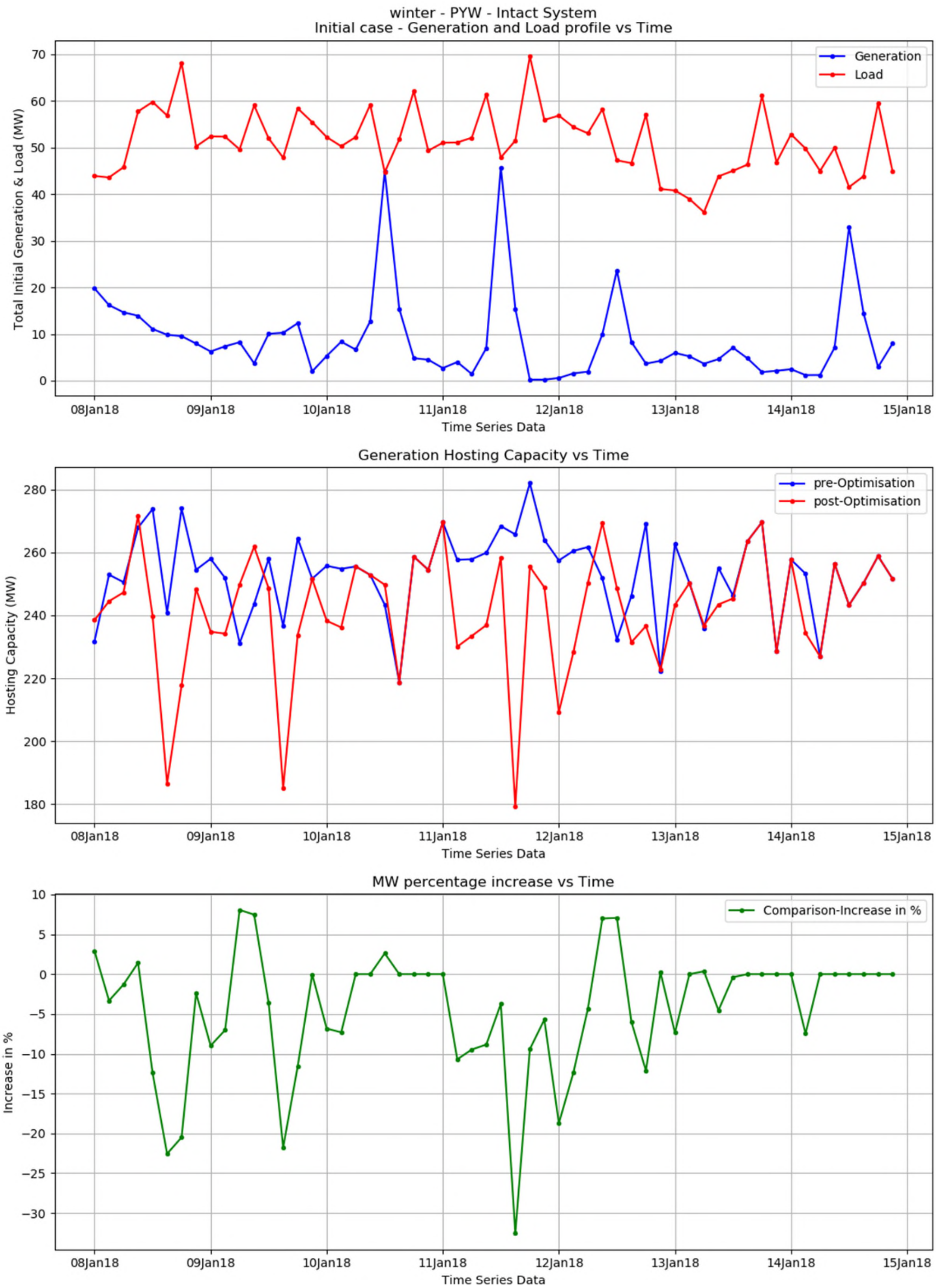
D.3.3. Intact System Autumn Week



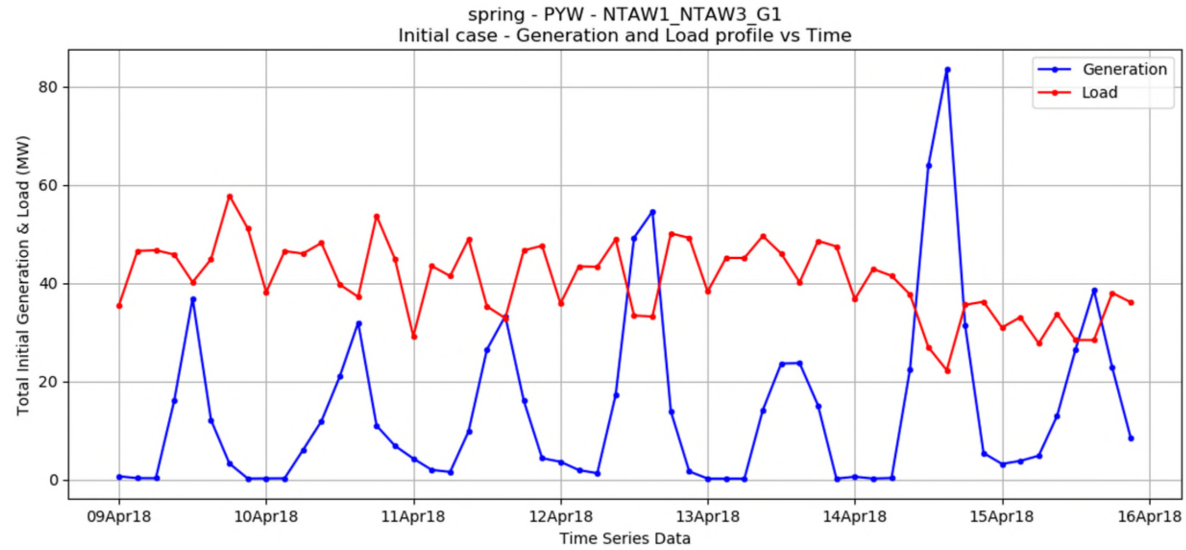


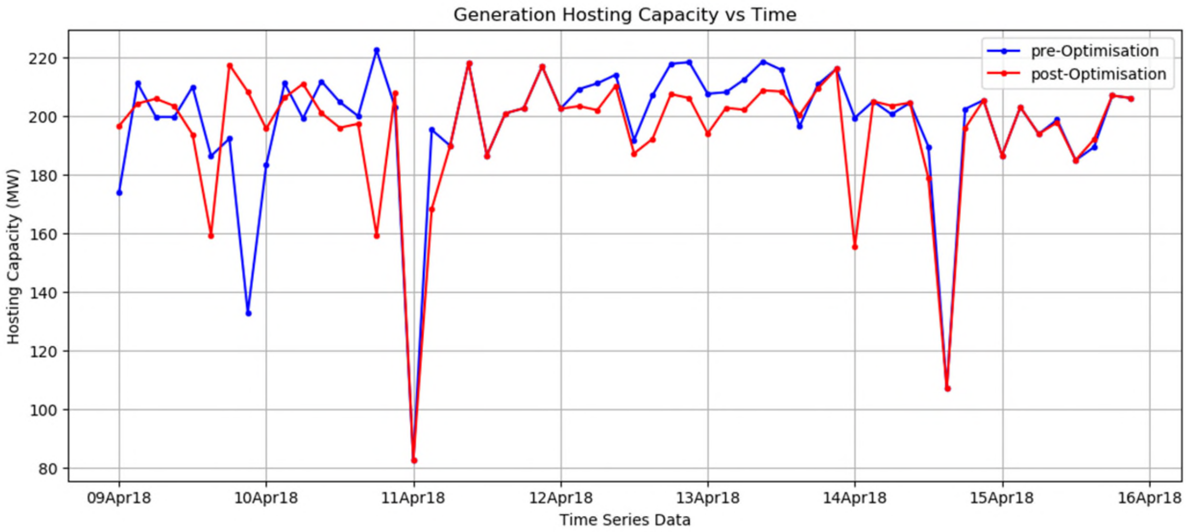


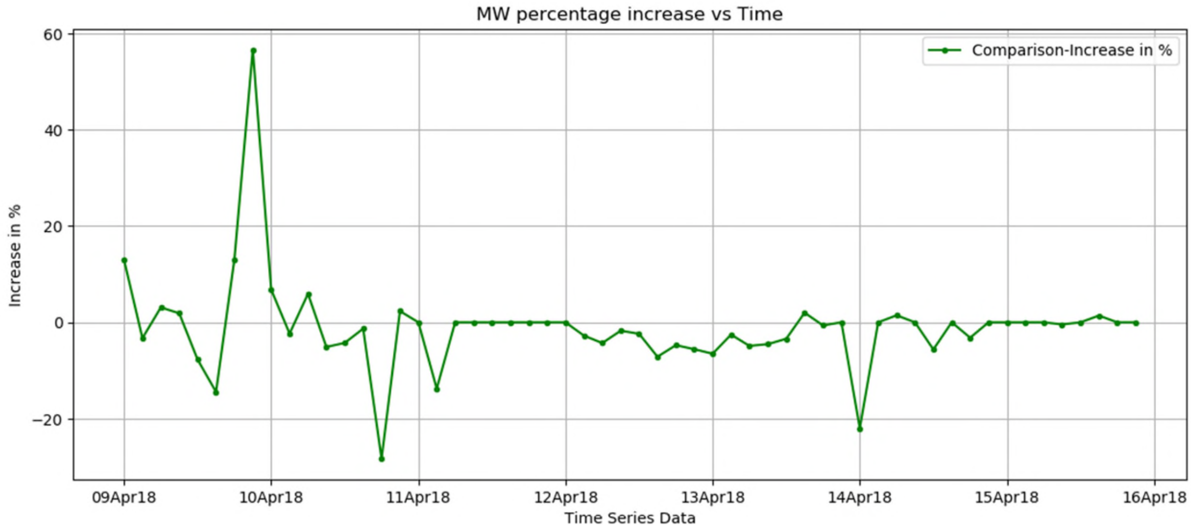
D.3.4. Intact System Winter Week



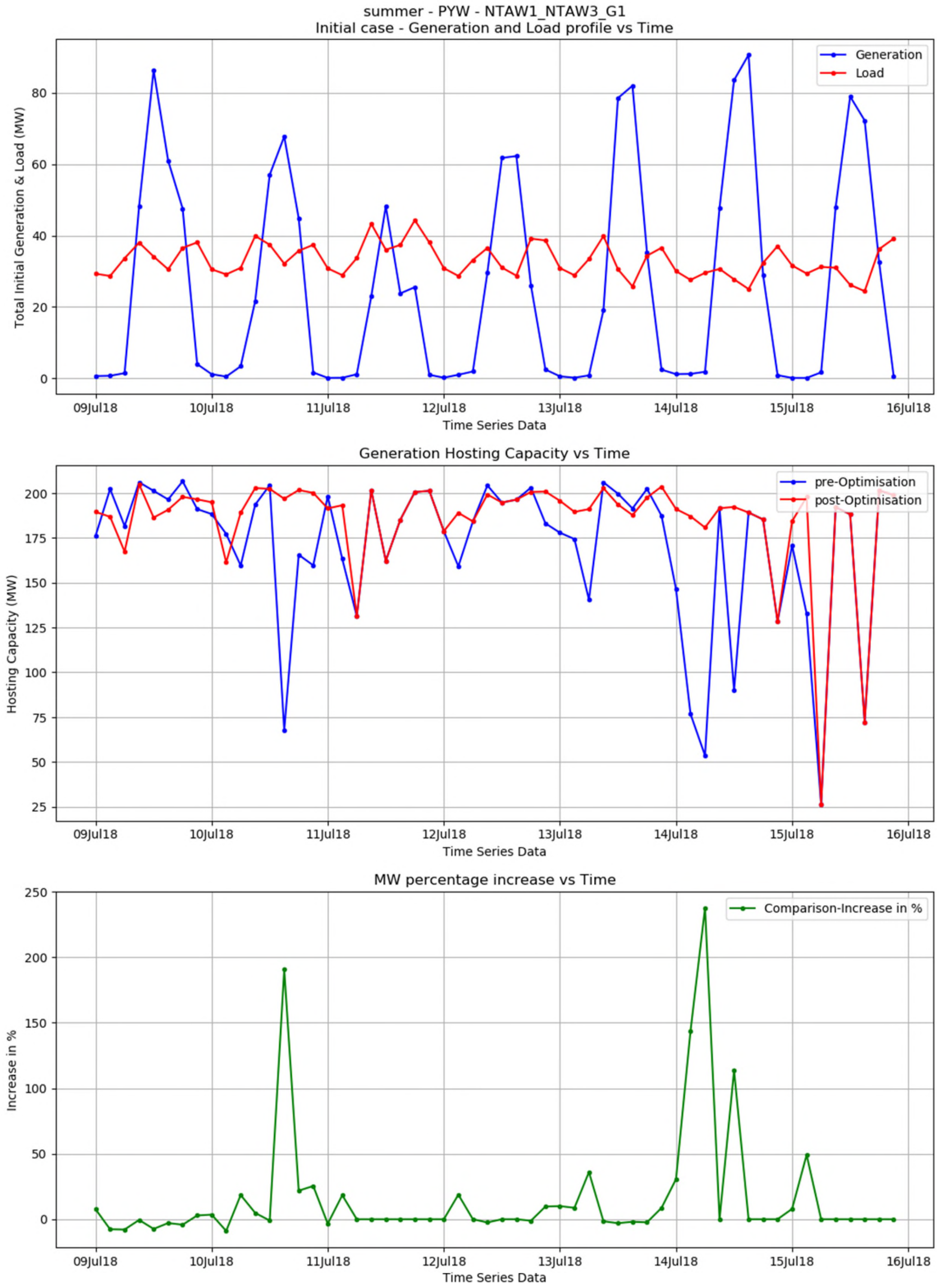
D.3.5. Worst Contingency NTAW1_NTAW3_G1 Spring Week



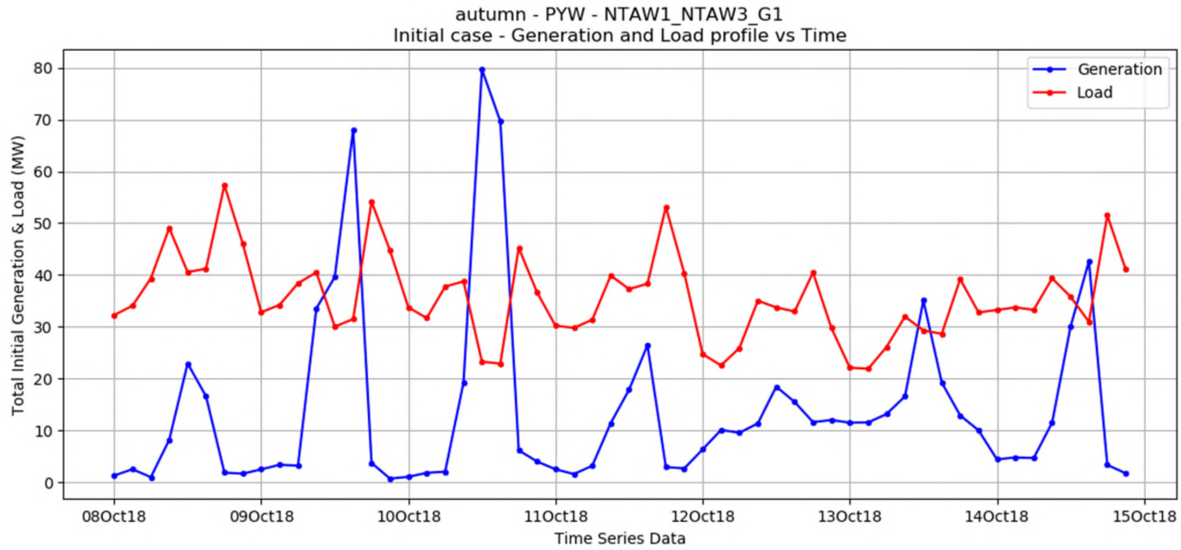


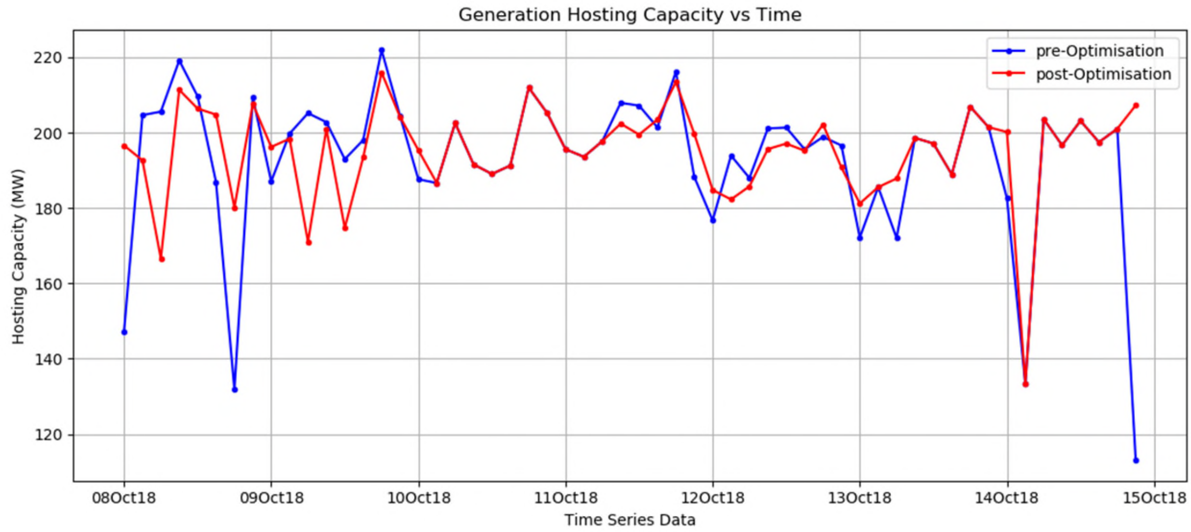


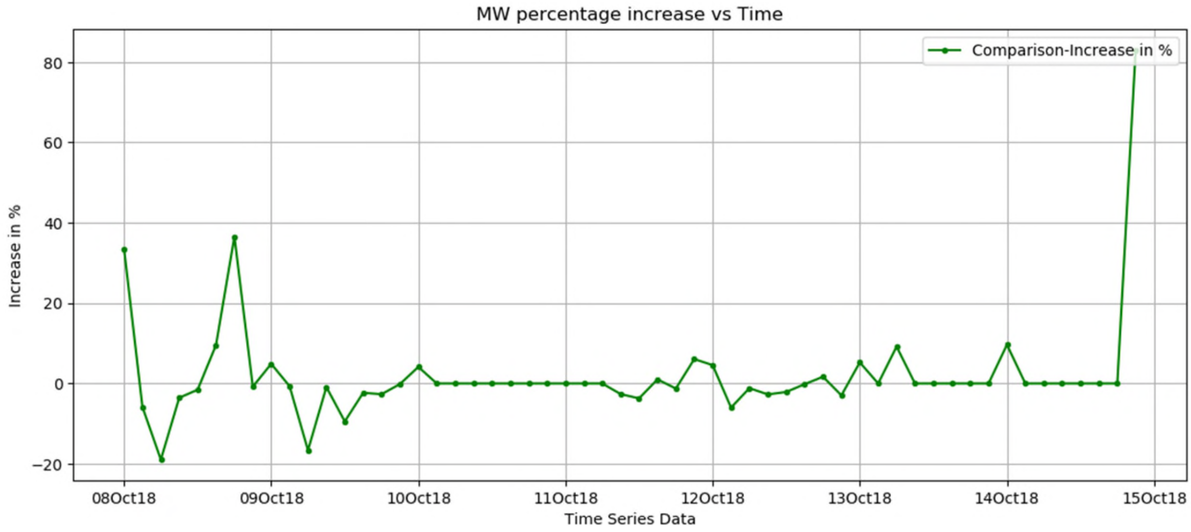
D.3.6. Worst Contingency NTAW1_NTAW3_G1 Summer Week



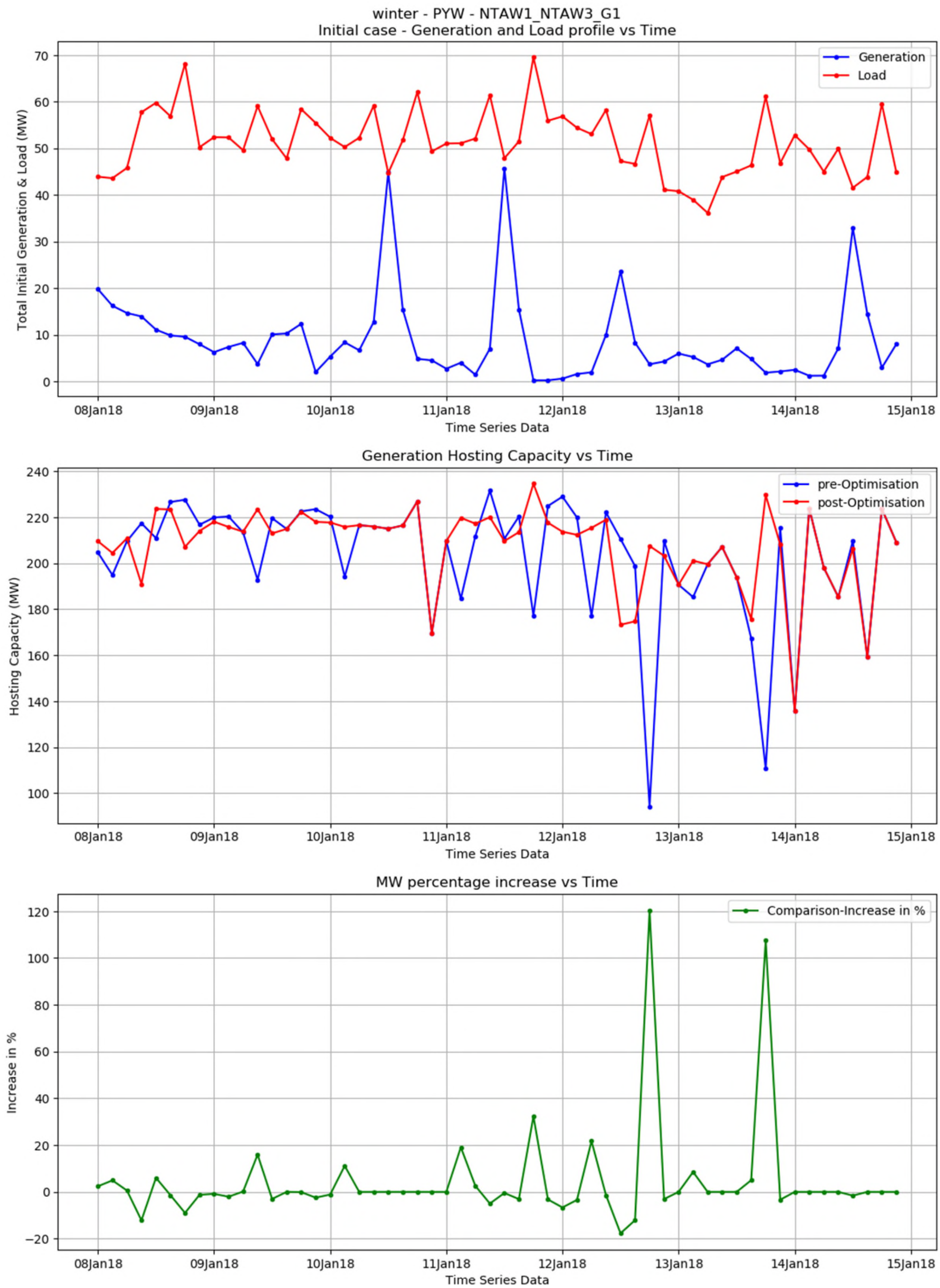
D.3.7. Worst Contingency NTAW1_NTAW3_G1 Autumn Week



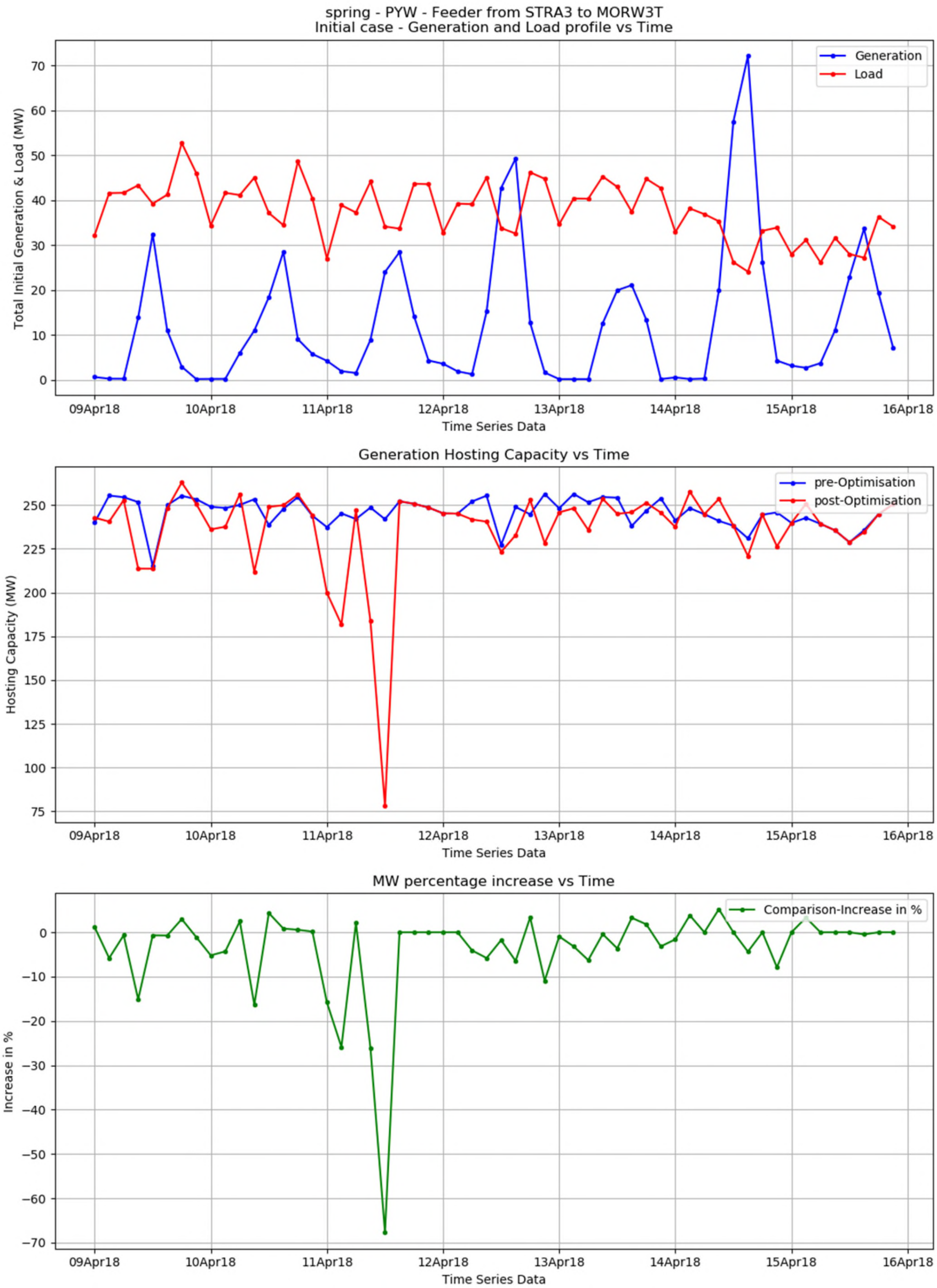




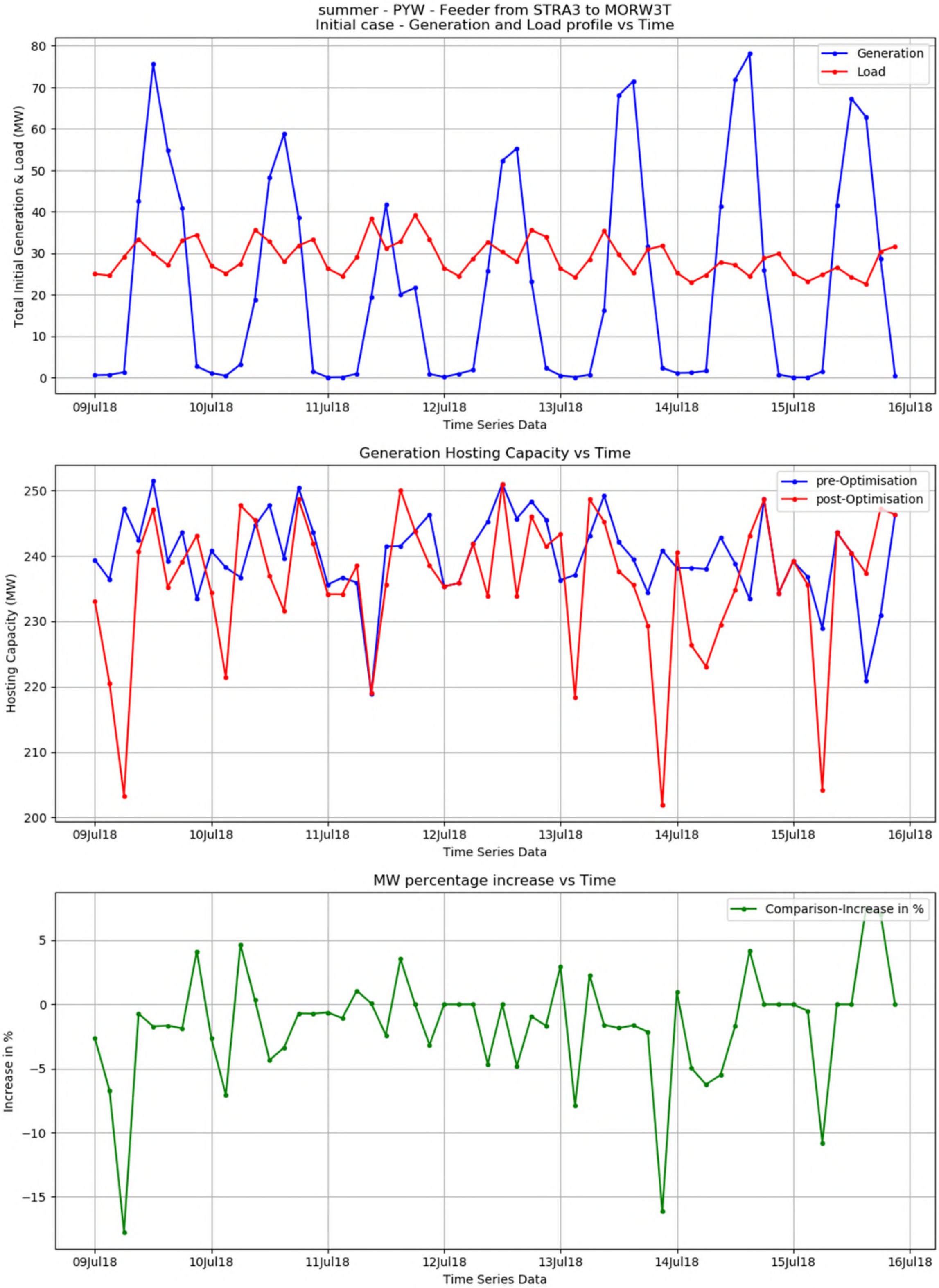
D.3.8. Worst Contingency NTAW1_NTAW3_G1 Winter Week



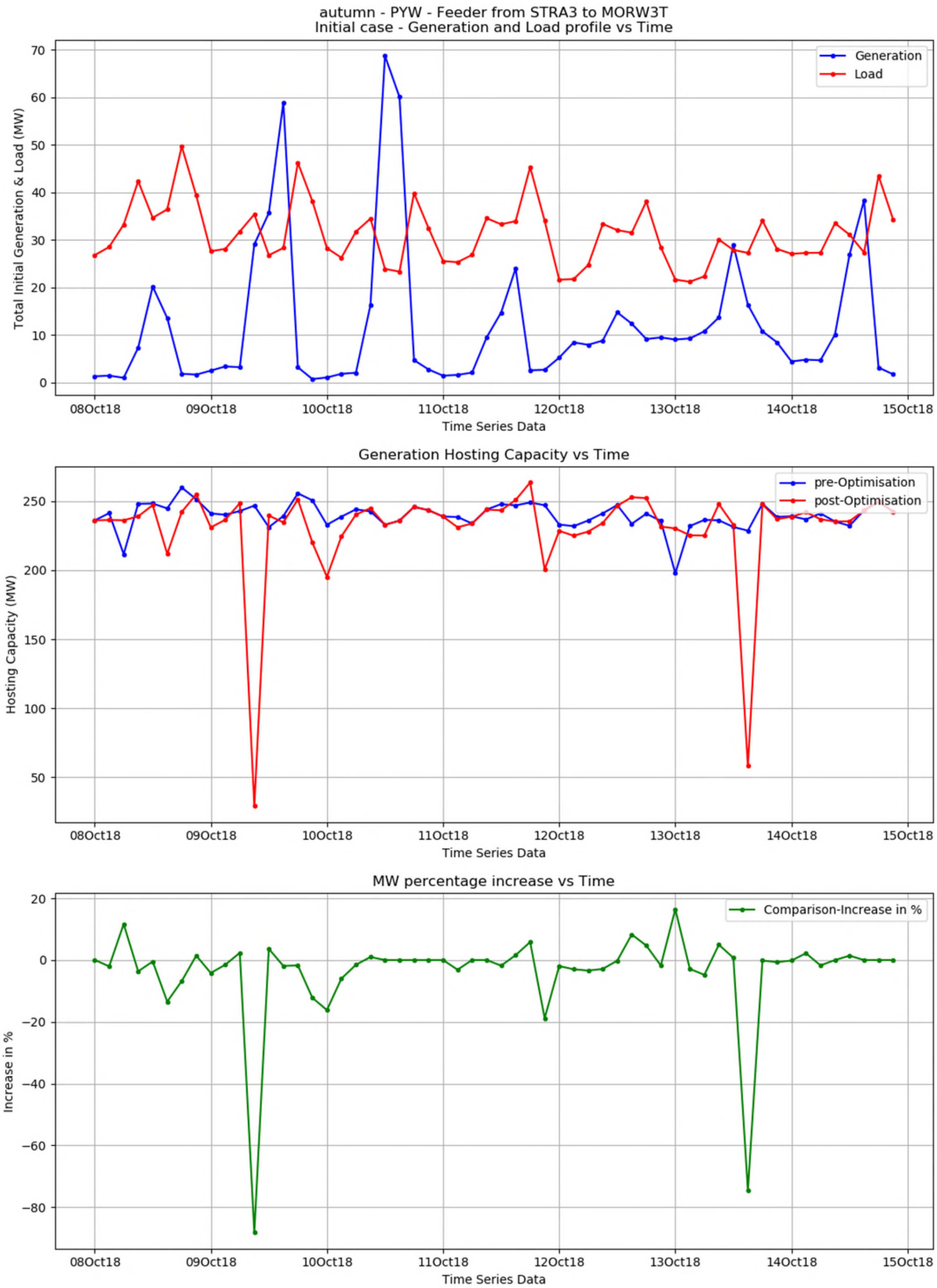
D.3.9. Best Contingency CLOV3K_FORE3T_L1+ ESLA3T_FORE3T_L2+ FORE3_FORE3T_L2+ MORW3_MORW3T_L1+ MORW3T_STRA3_L1+ MORW3T_ESLA3T_L1+ ESLA3_ESLA3T_L1 Spring Week



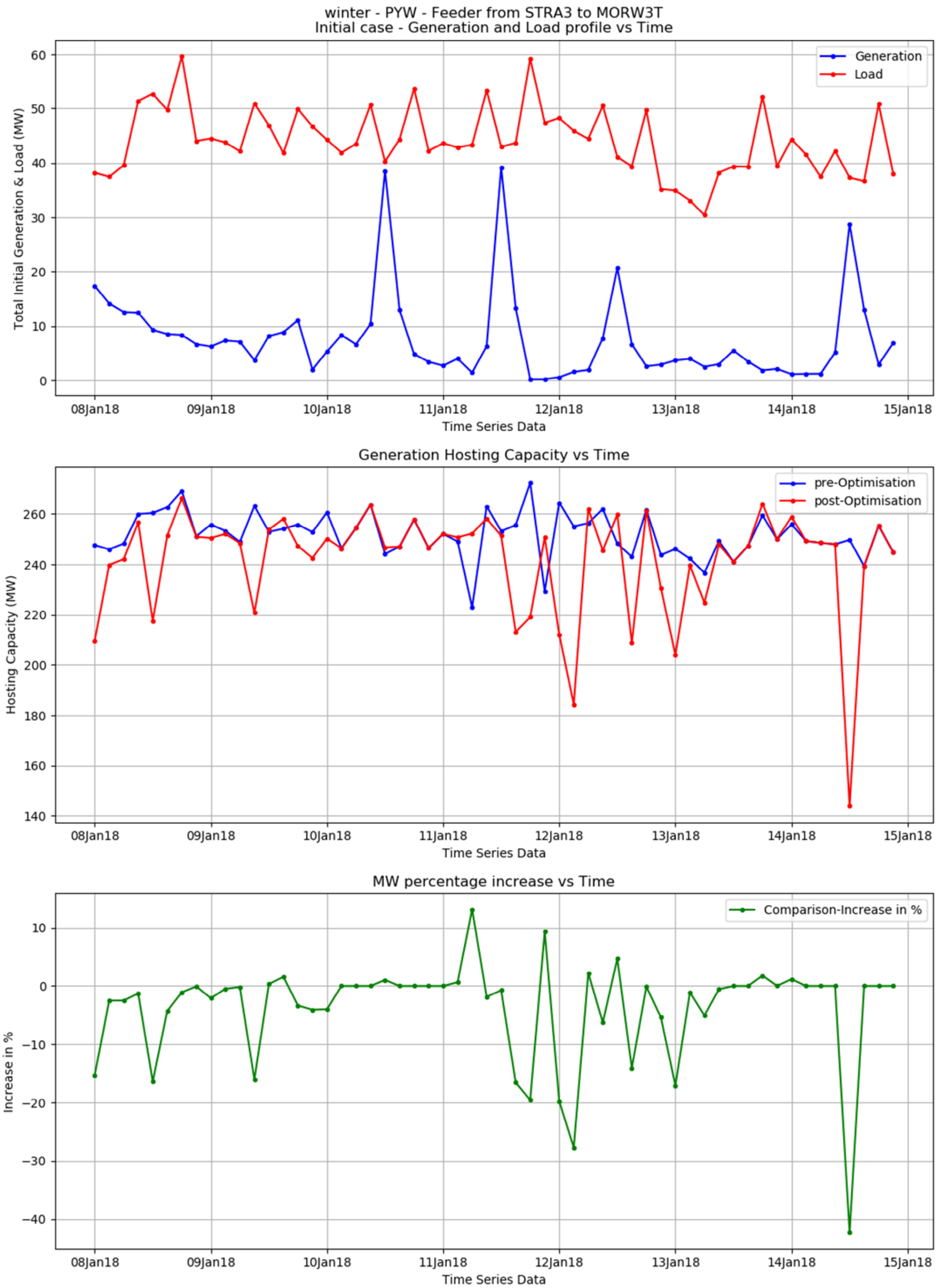
D.3.10. Best Contingency CLOV3K_FORE3T_L1+ ESLA3T_FORE3T_L2+ FORE3_FORE3T_L2+ MORW3_MORW3T_L1+ MORW3T_STRA3_L1+ MORW3T_ESLA3T_L1+ ESLA3_ESLA3T_L1 Summer Week



D.3.11. Best Contingency CLOV3K_FORE3T_L1+ ESLA3T_FORE3T_L2+ FORE3_FORE3T_L2+ MORW3_MORW3T_L1+ MORW3T_STRA3_L1+ MORW3T_ESLA3T_L1+ ESLA3_ESLA3T_L1 Autumn Week



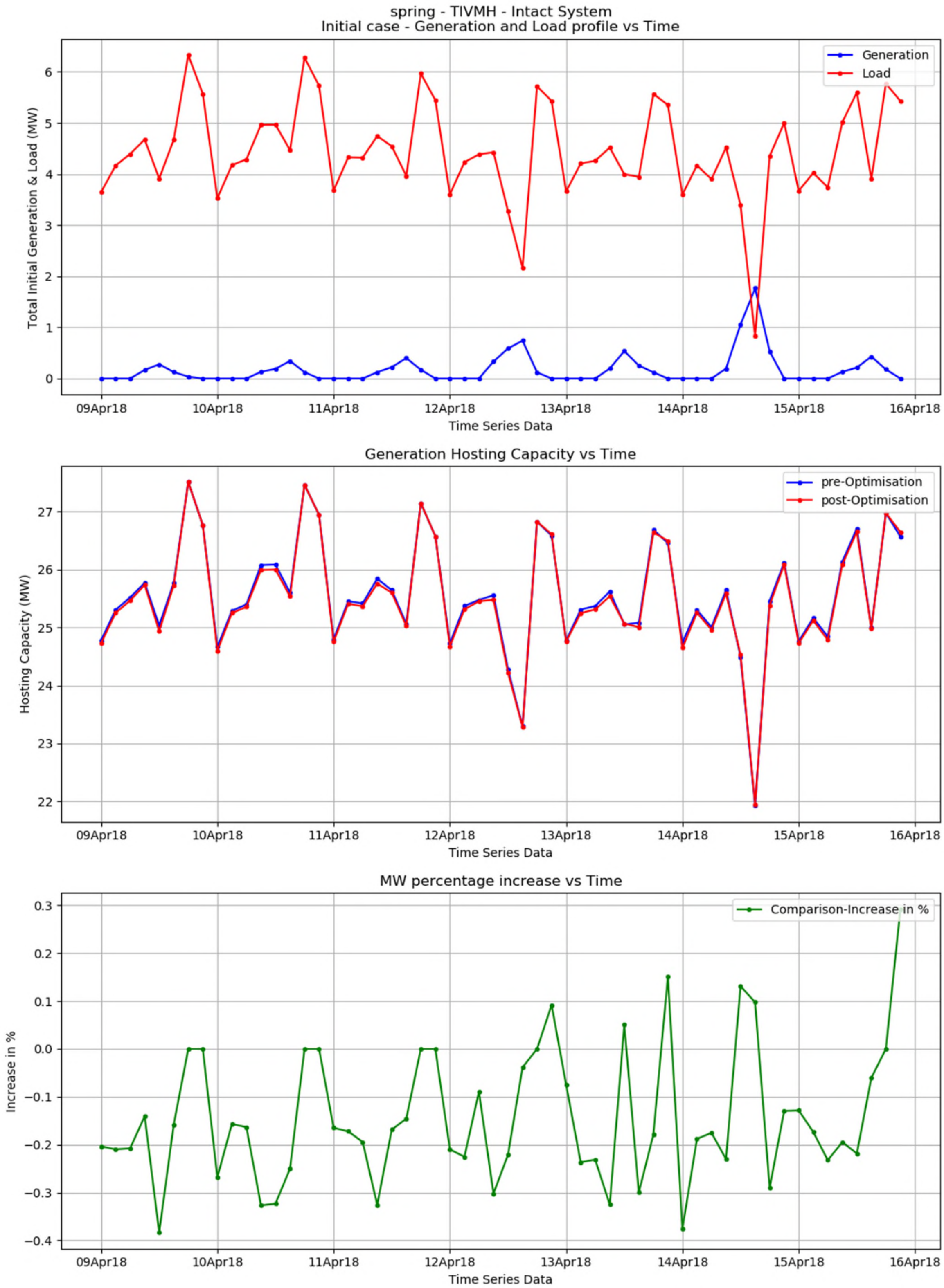
D.3.12. Best Contingency CLOV3K_FORE3T_L1+ ESLA3T_FORE3T_L2+ FORE3_FORE3T_L2+ MORW3_MORW3T_L1+ MORW3T_STRA3_L1+ MORW3T_ESLA3T_L1+ ESLA3_ESLA3T_L1 Winter Week



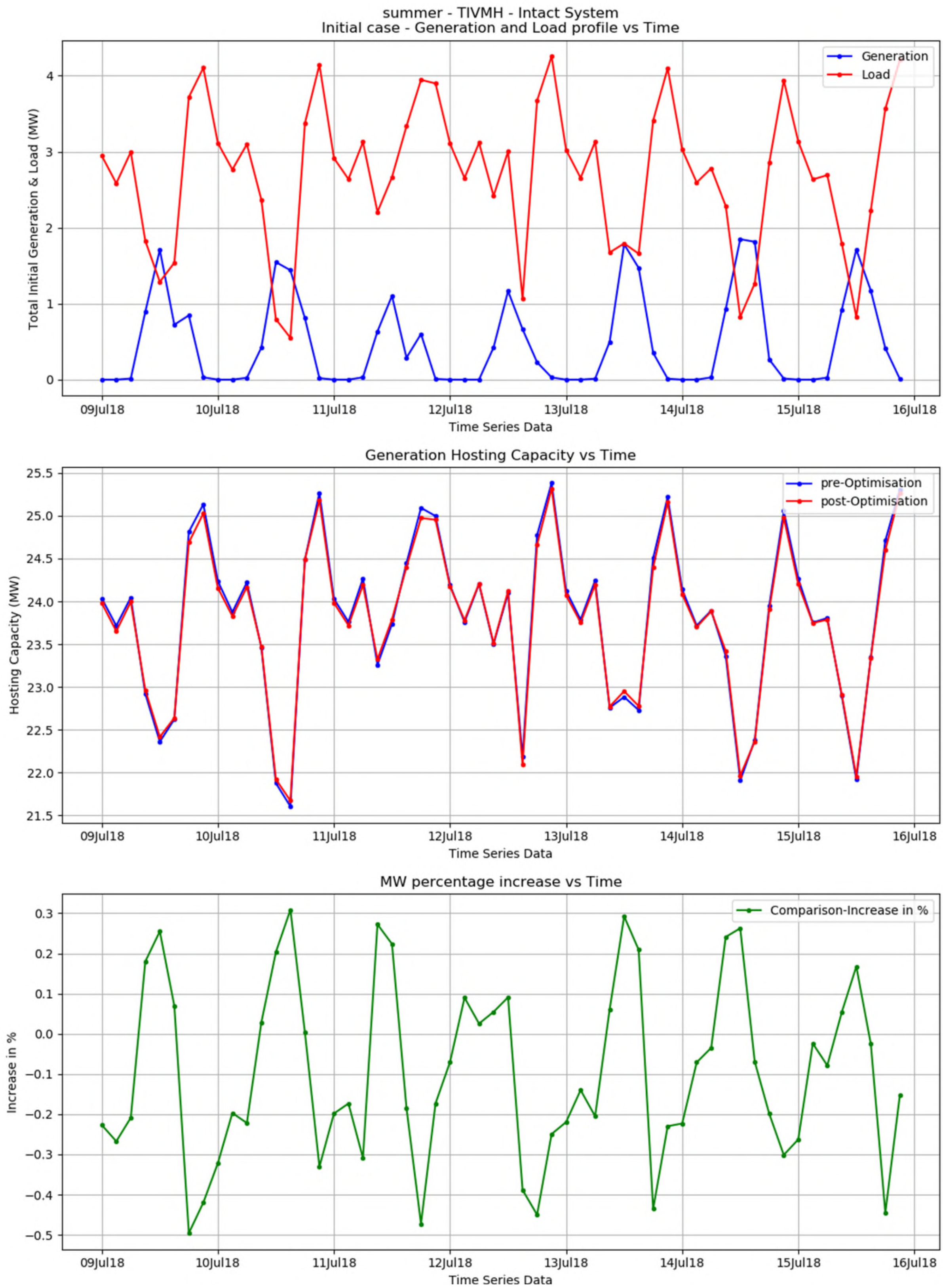
D.4. Tiverton Moorhayes 11 kV Primary

Note: A incorrect time step selection lead to no results from 9/4/18 9am to 11/4/18 9 am.

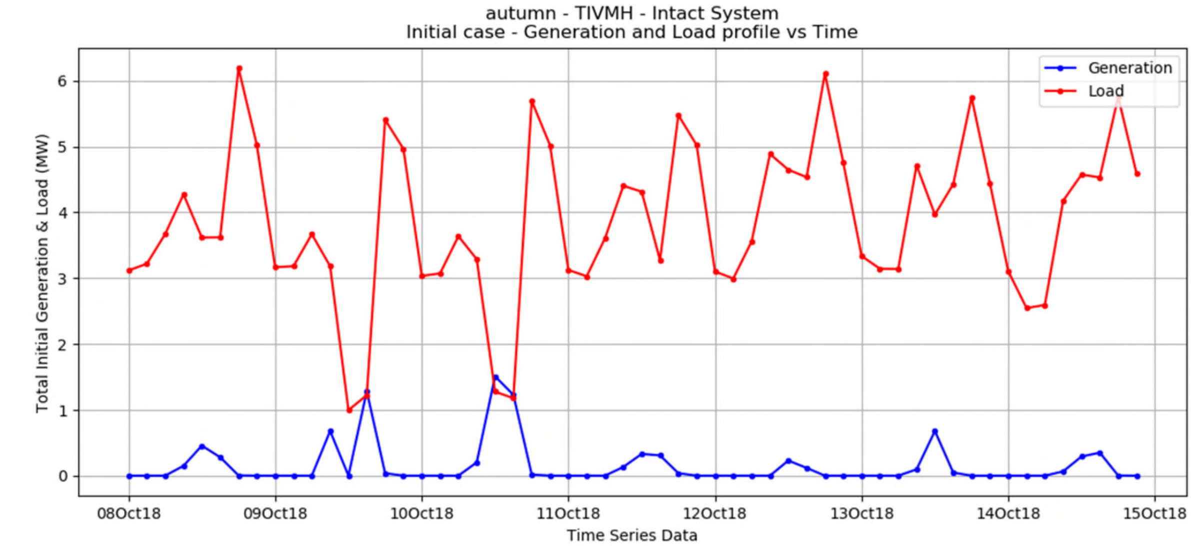
D.4.1. Intact System Spring Week

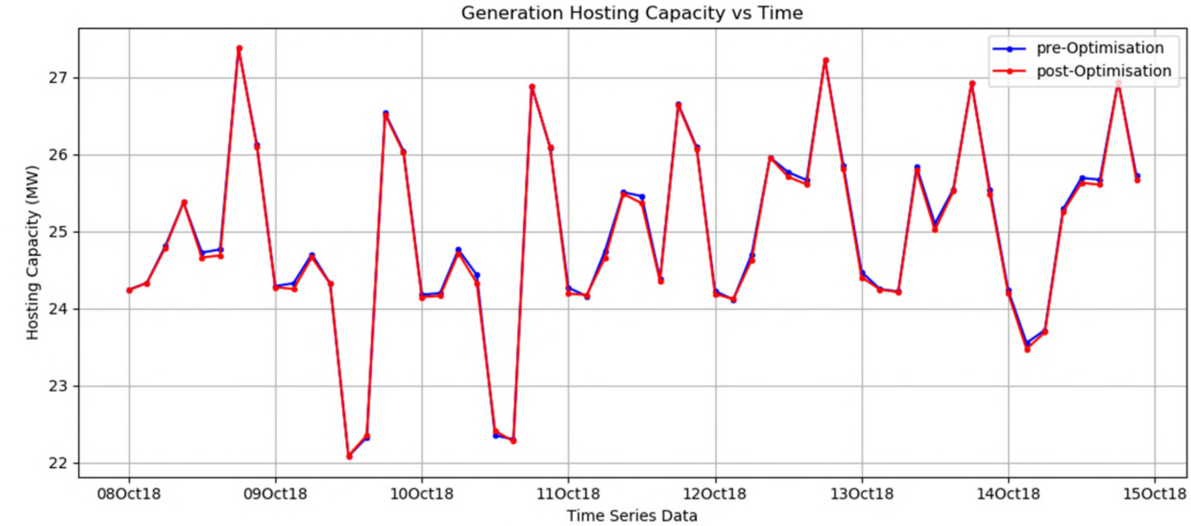


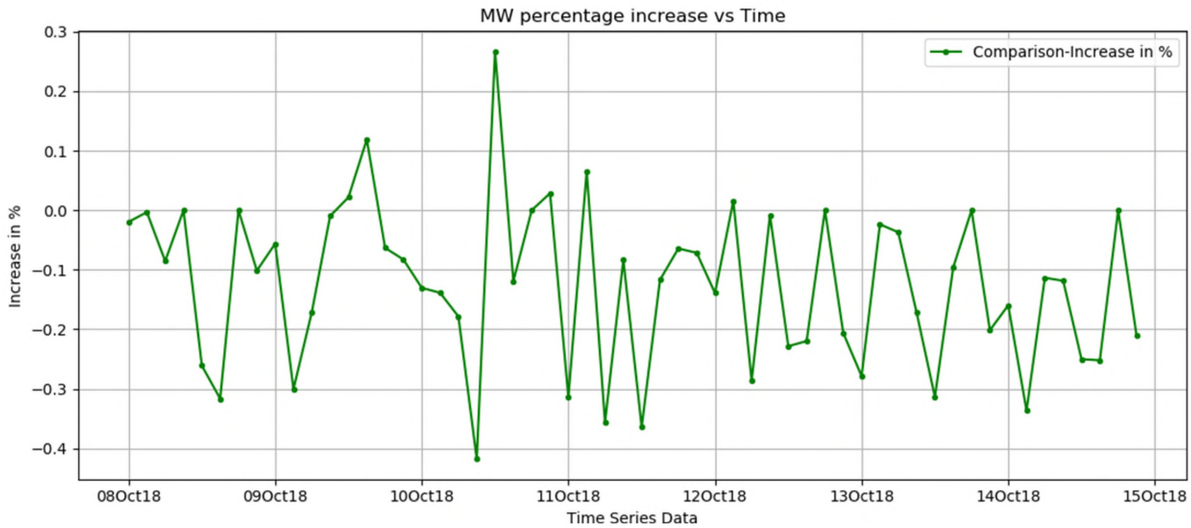
D.4.2. Intact System Summer Week



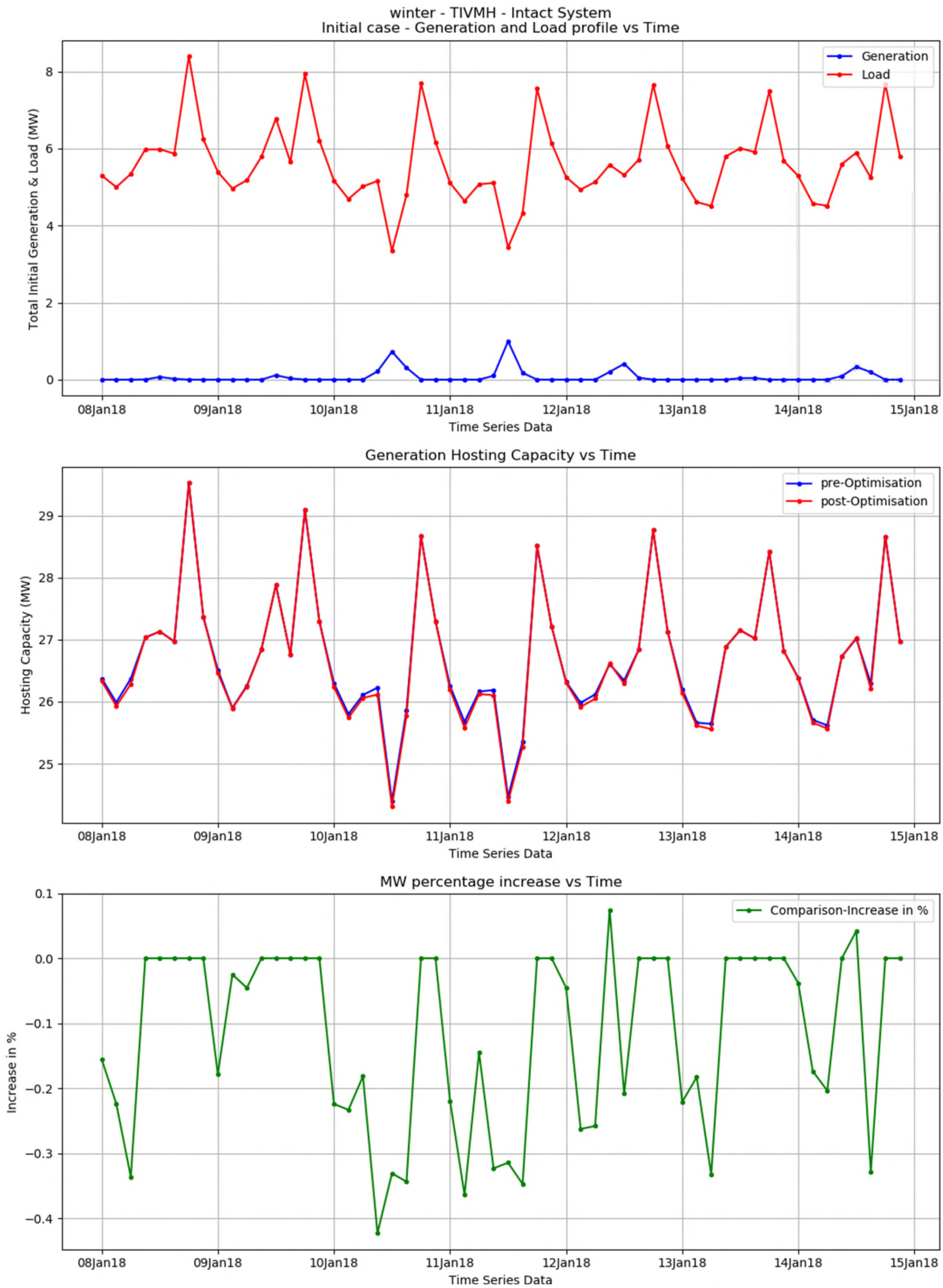
D.4.3. Intact System Autumn Week



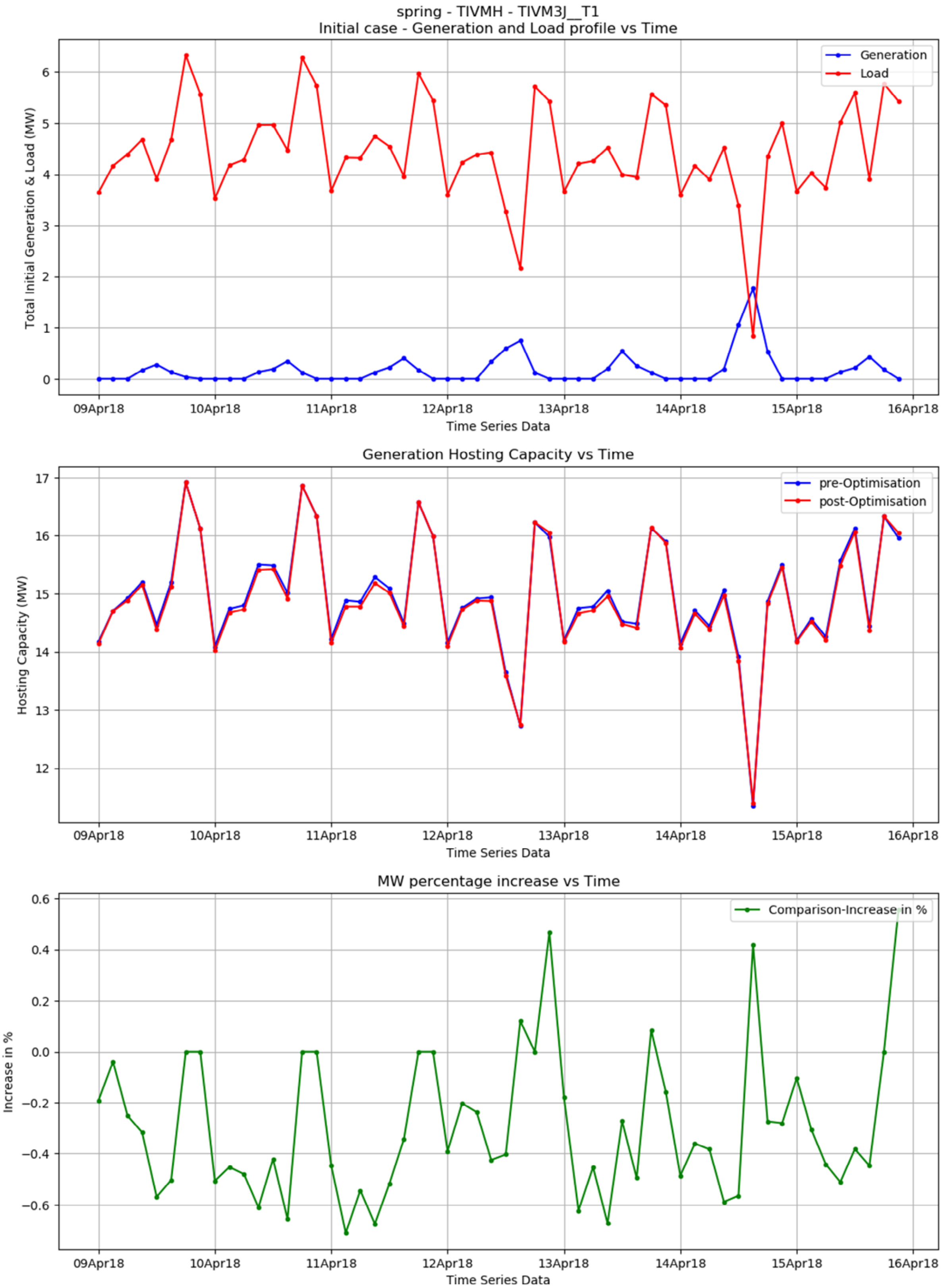




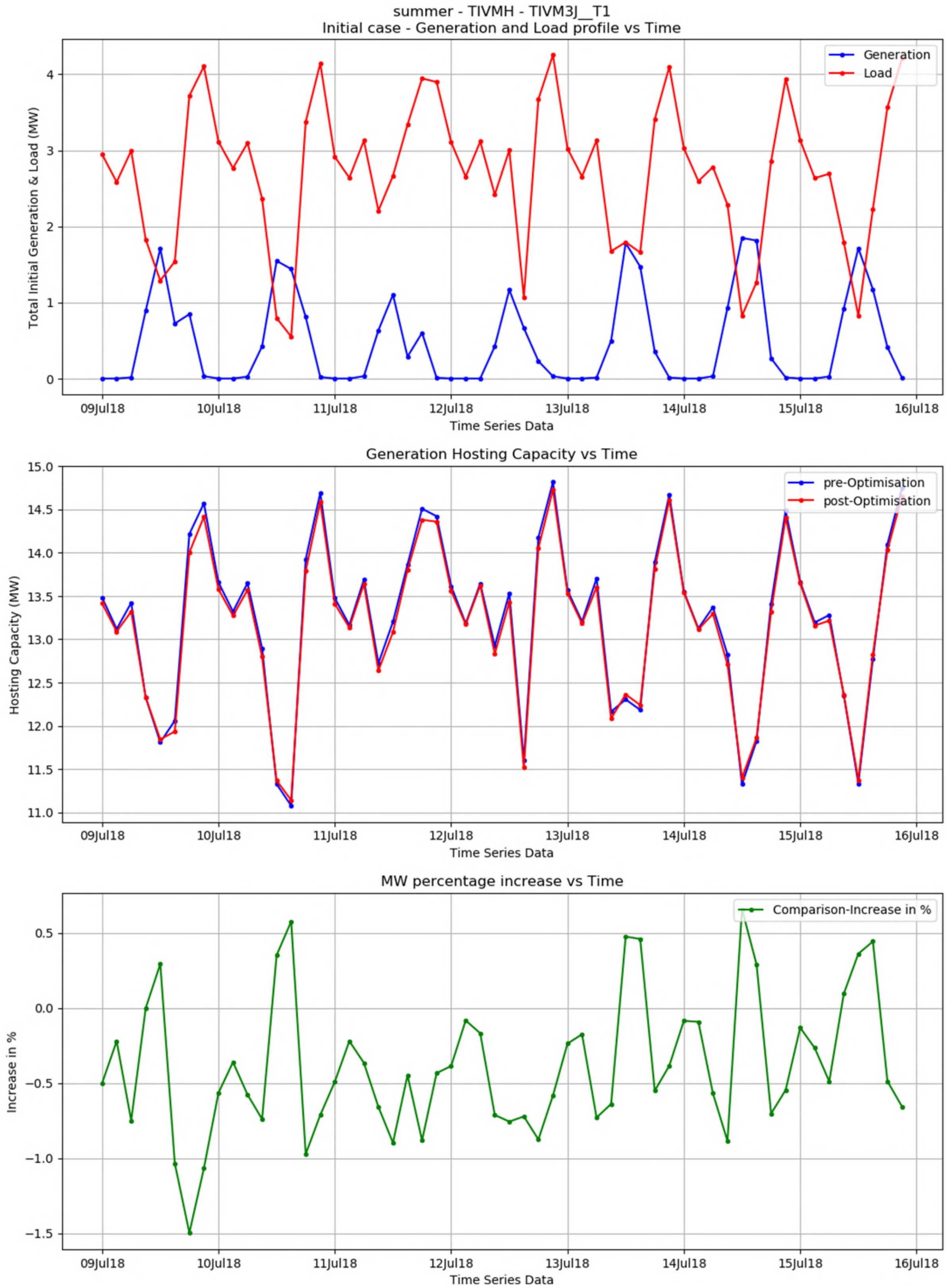
D.4.4. Intact System Winter Week



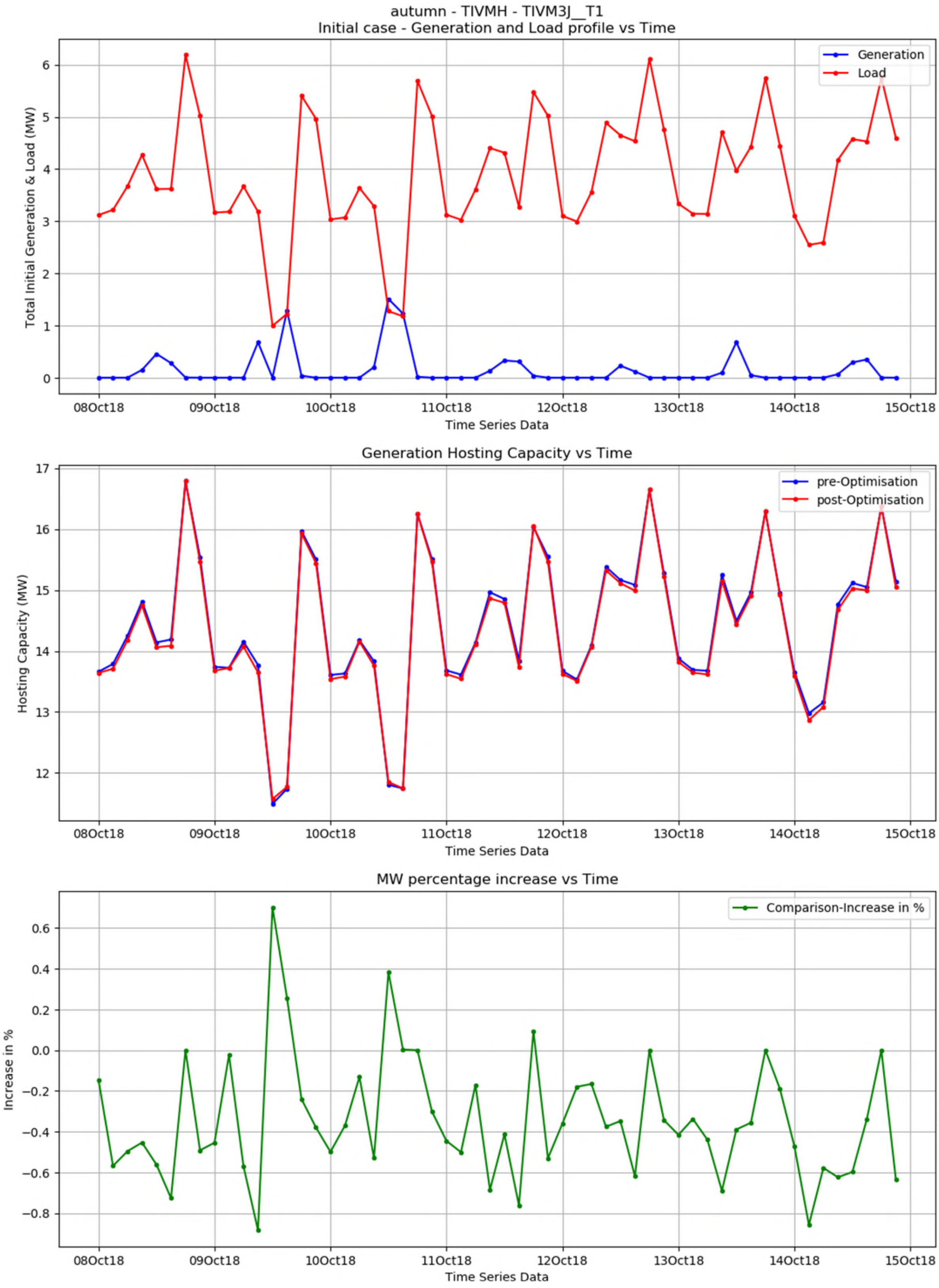
D.4.5. Worst Contingency TIVM3J__T1 Spring Week



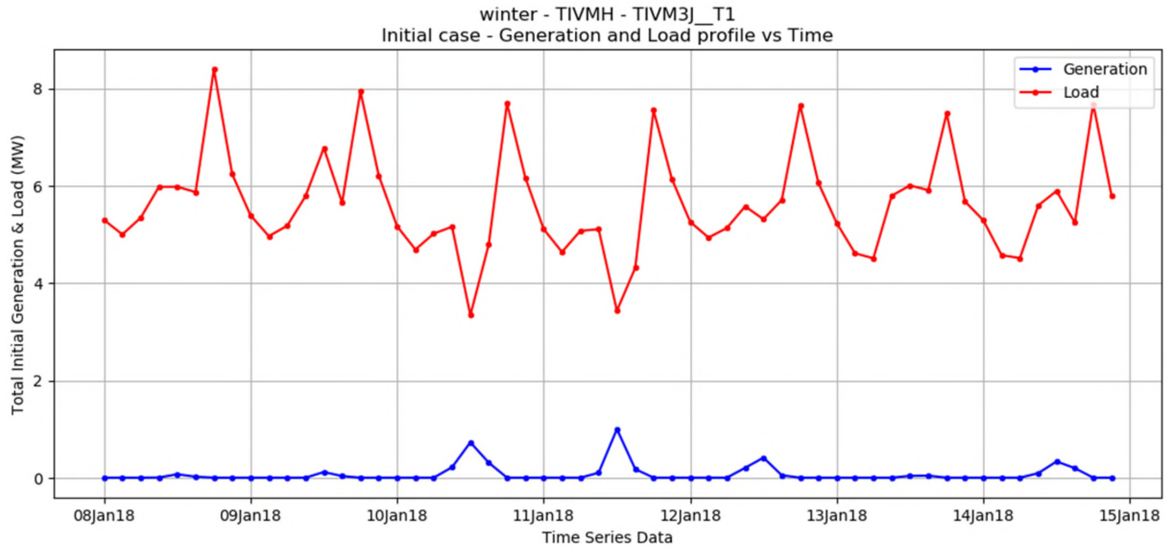
D.4.6. Worst Contingency TIVM3J__T1 Summer Week

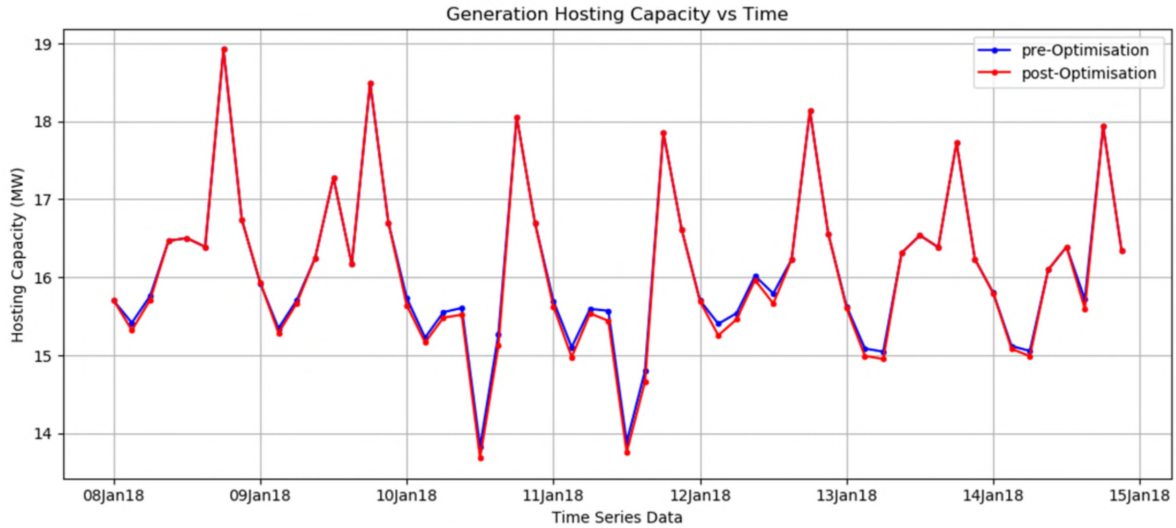


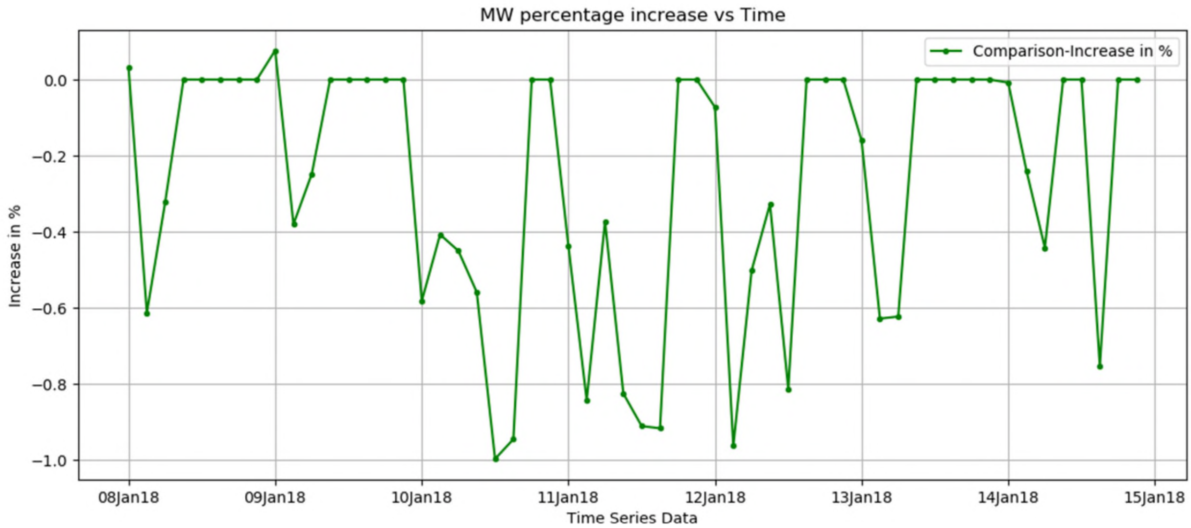
D.4.7. Worst Contingency TIVM3J__T1 Autumn Week



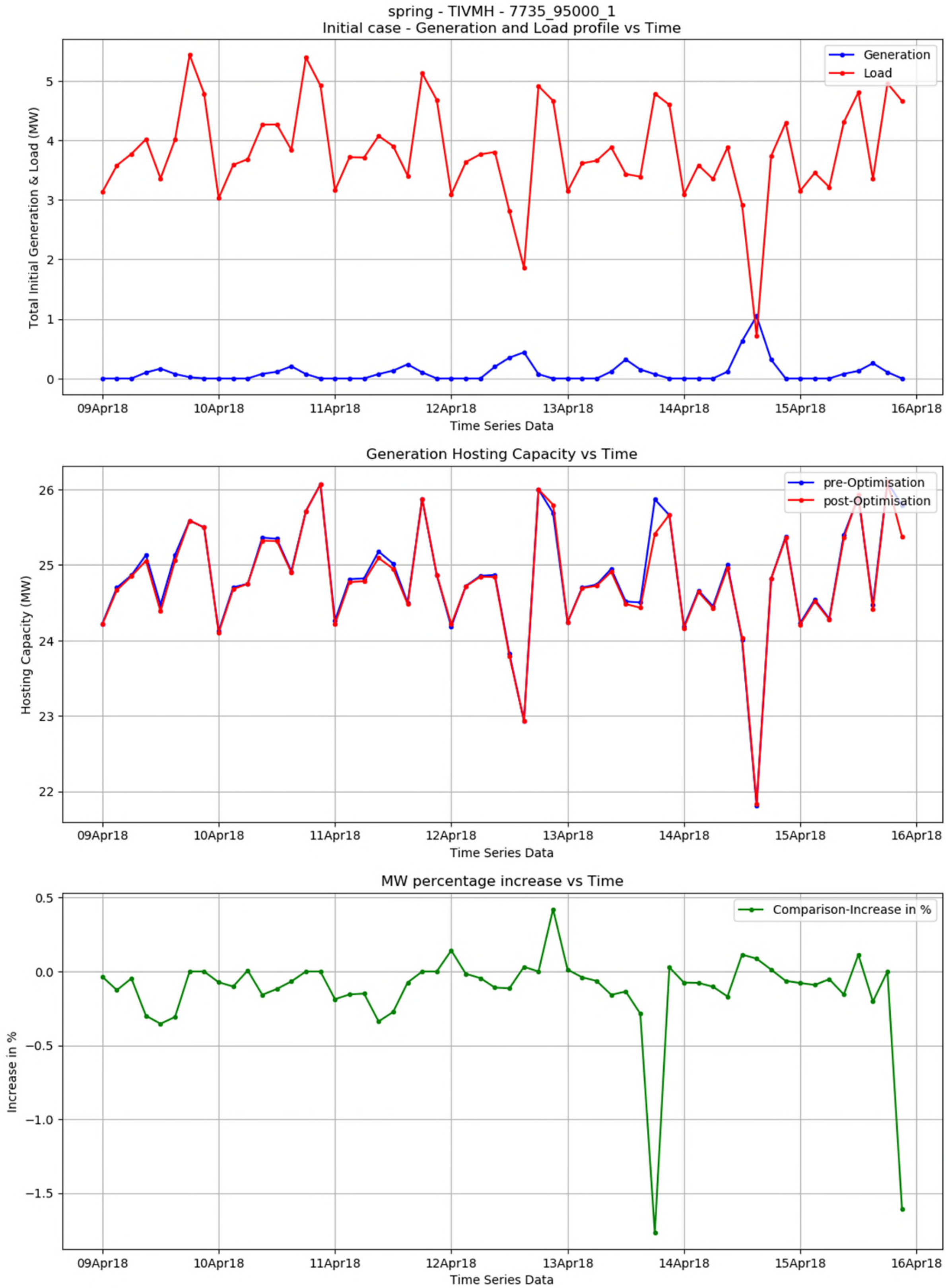
D.4.8. Worst Contingency TIVM3J__T1 Winter Week



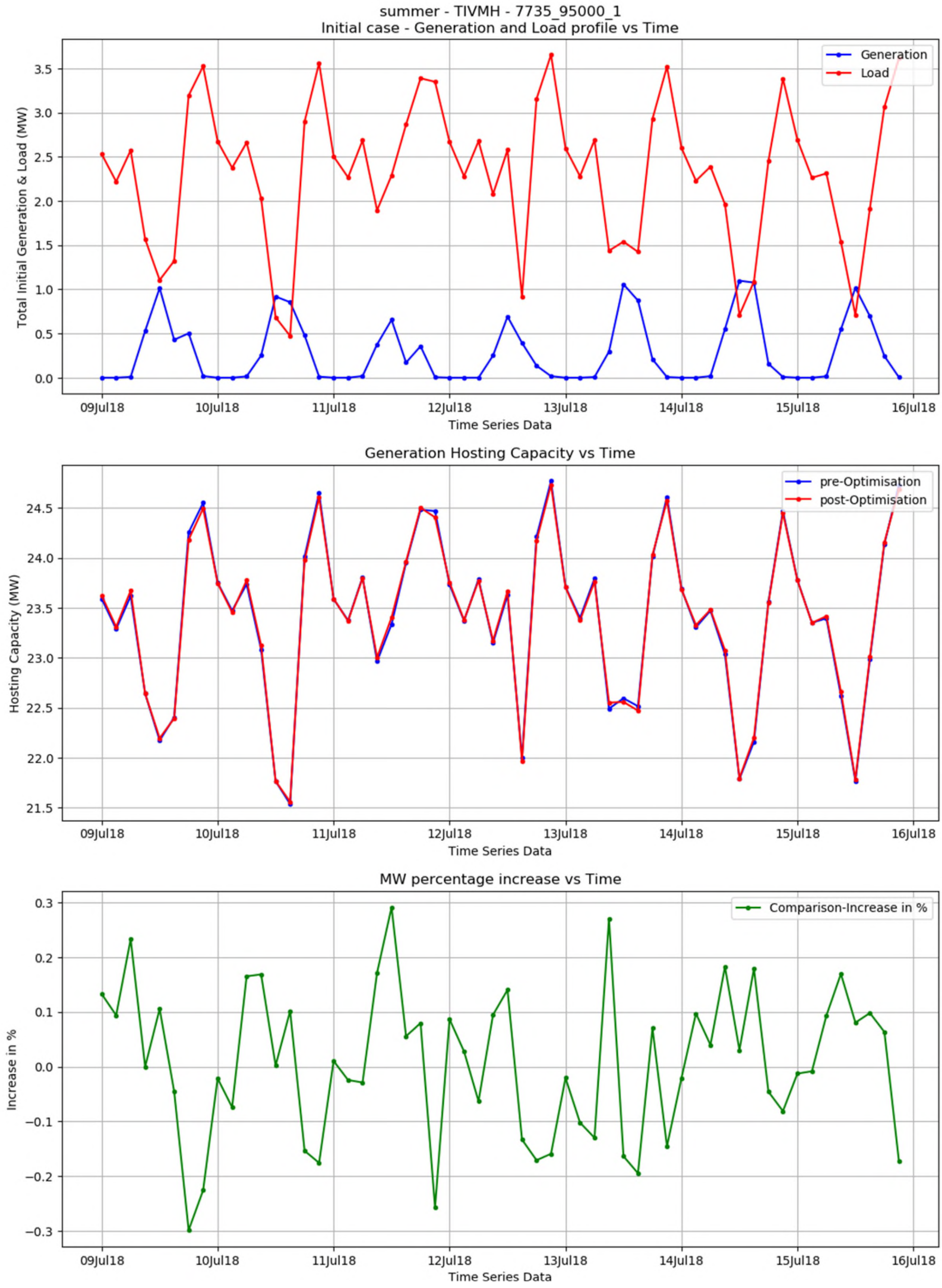




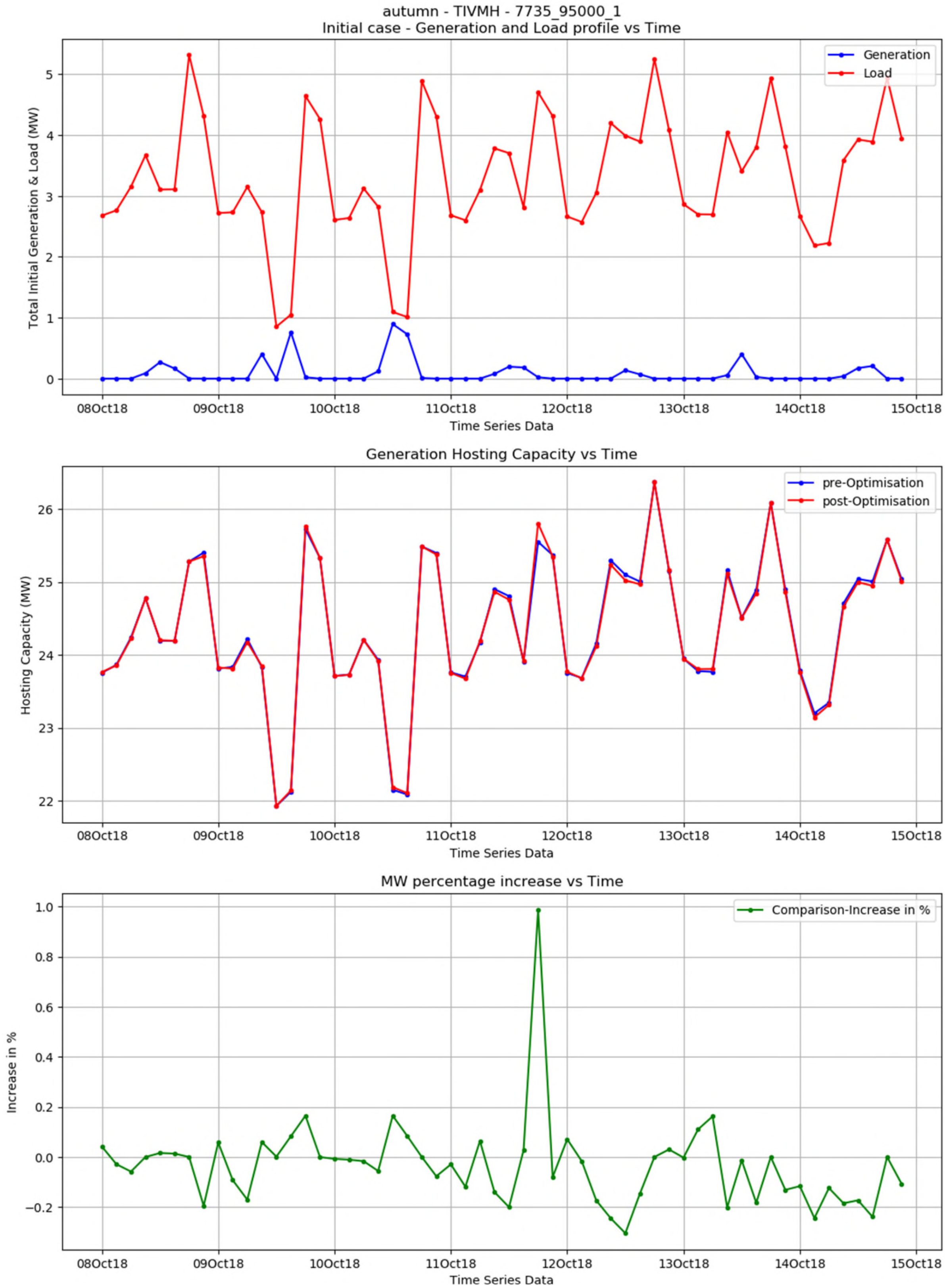
D.4.9. Best Contingency 7735_95000_1 Spring Week



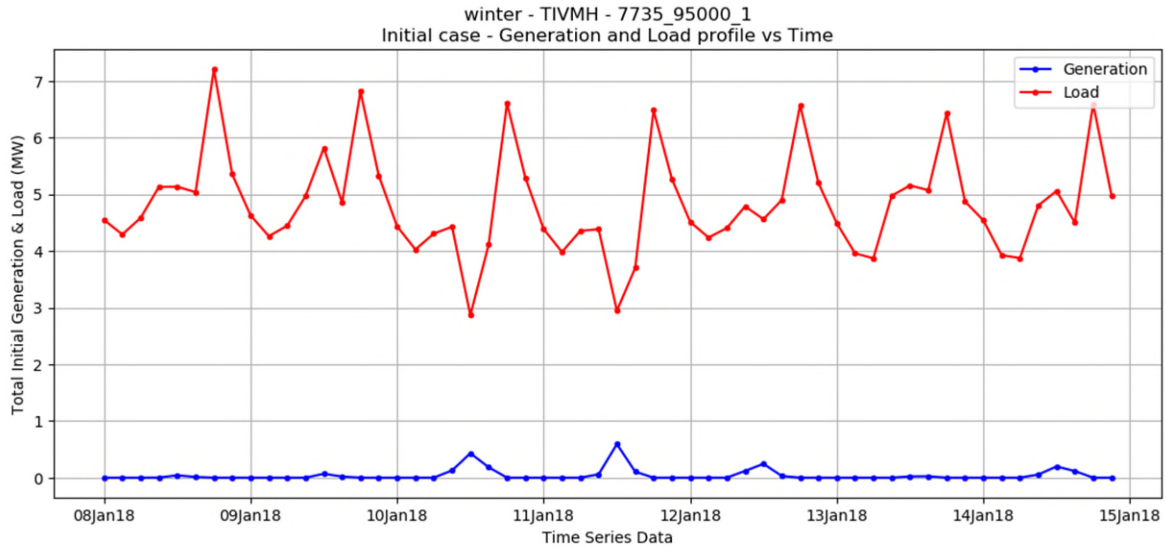
D.4.10. Best Contingency 7735_95000_1 Summer Week

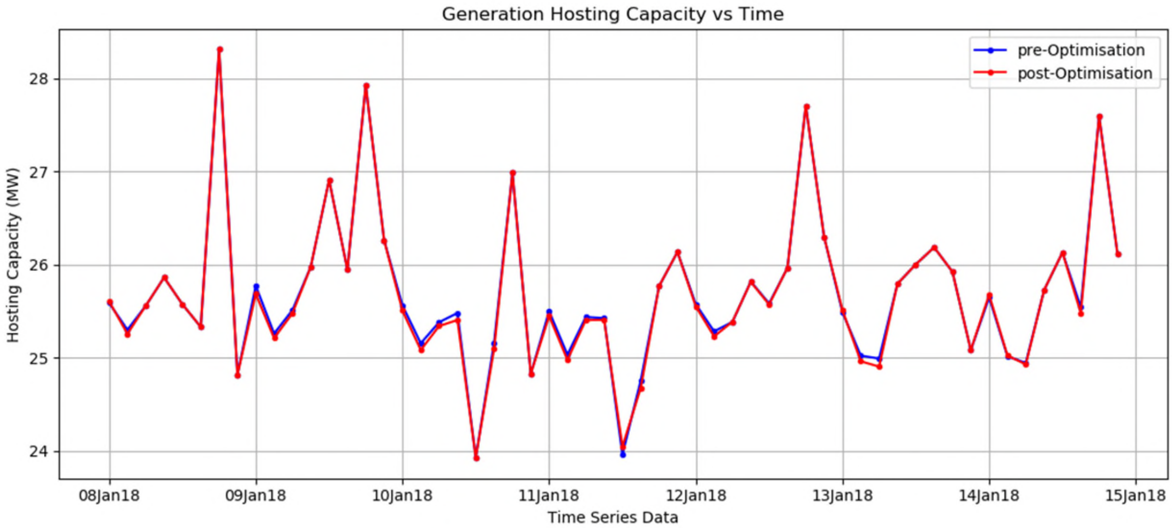


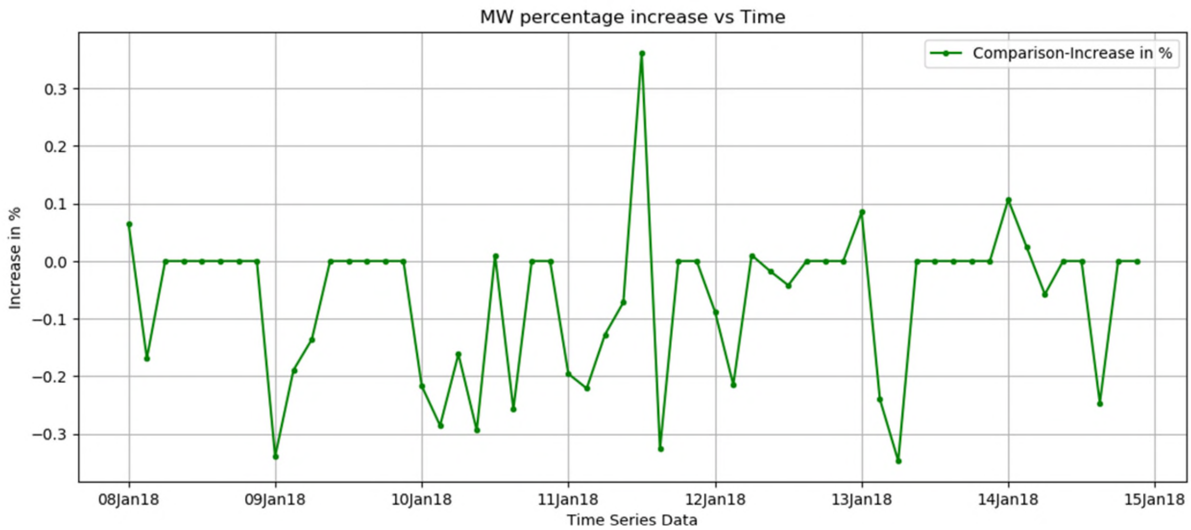
D.4.11. Best Contingency 7735_95000_1 Autumn Week



D.4.12. Best Contingency 7735_95000_1 Winter Week



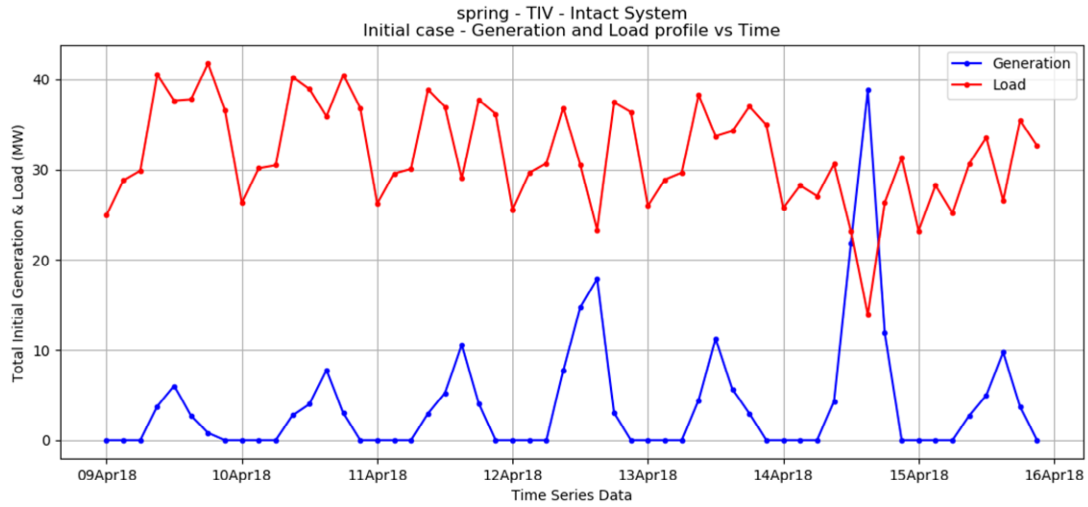


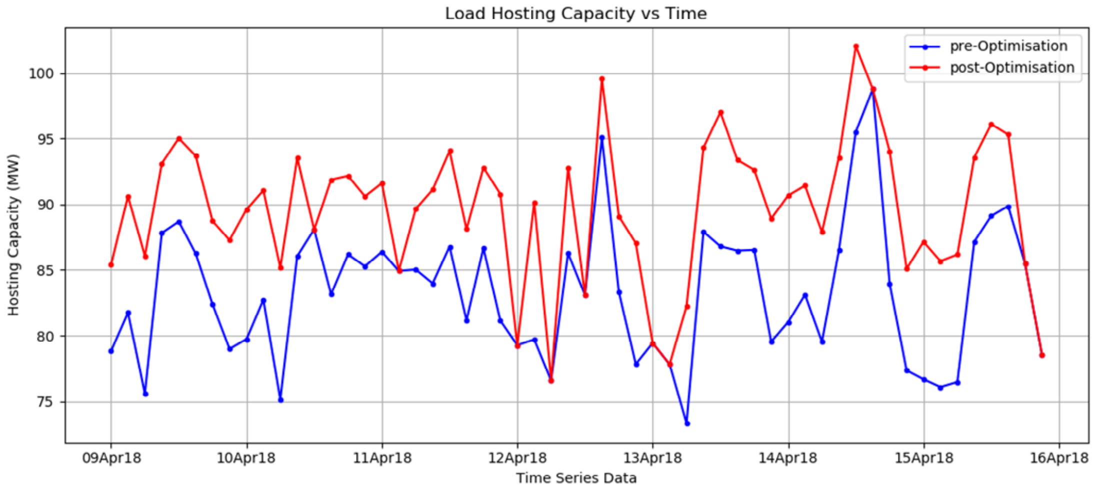


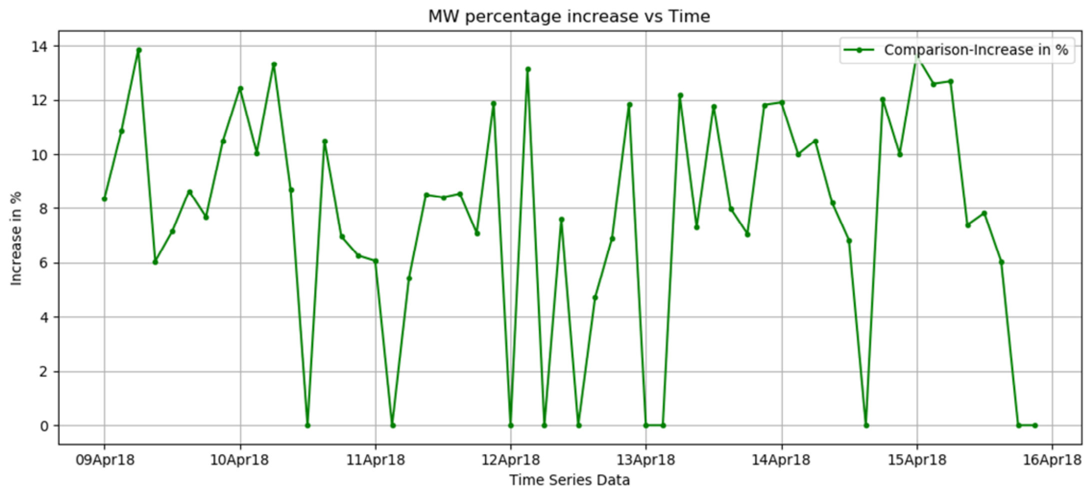
Appendix E Time Series Studies Load Hosting Results

E.1. Tiverton 33 kV BSP

E.1.1. Intact System Spring Week

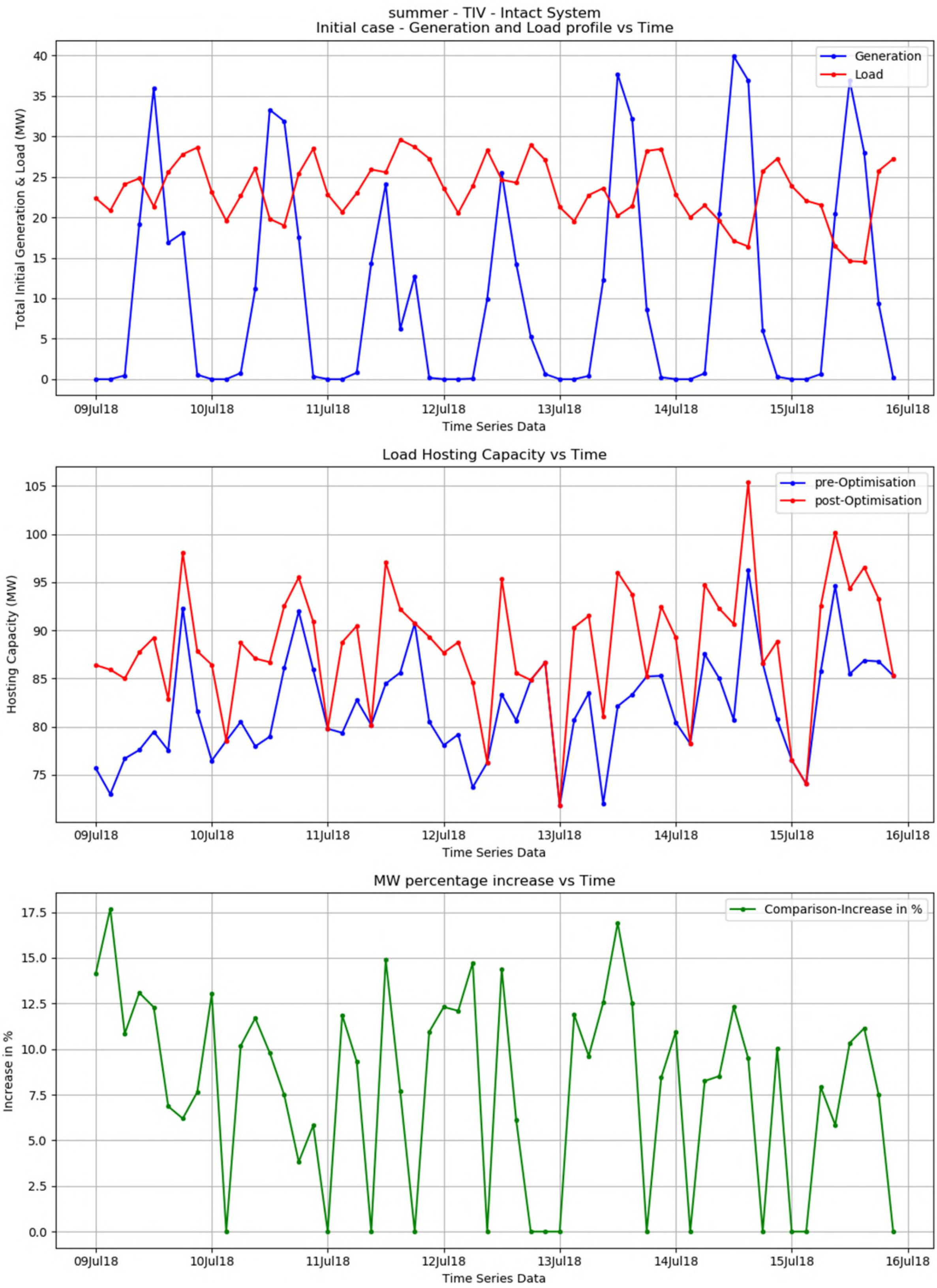




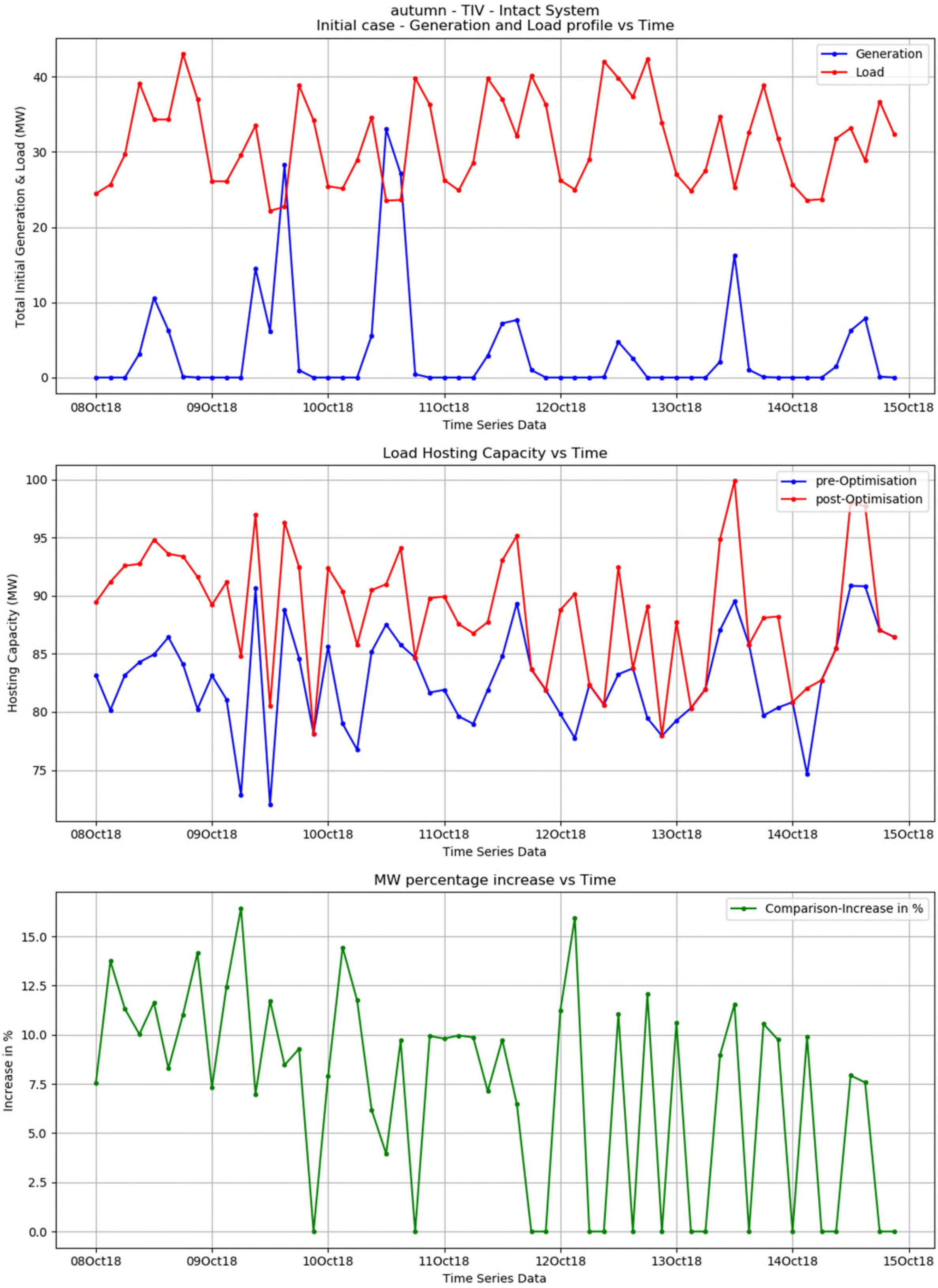


.

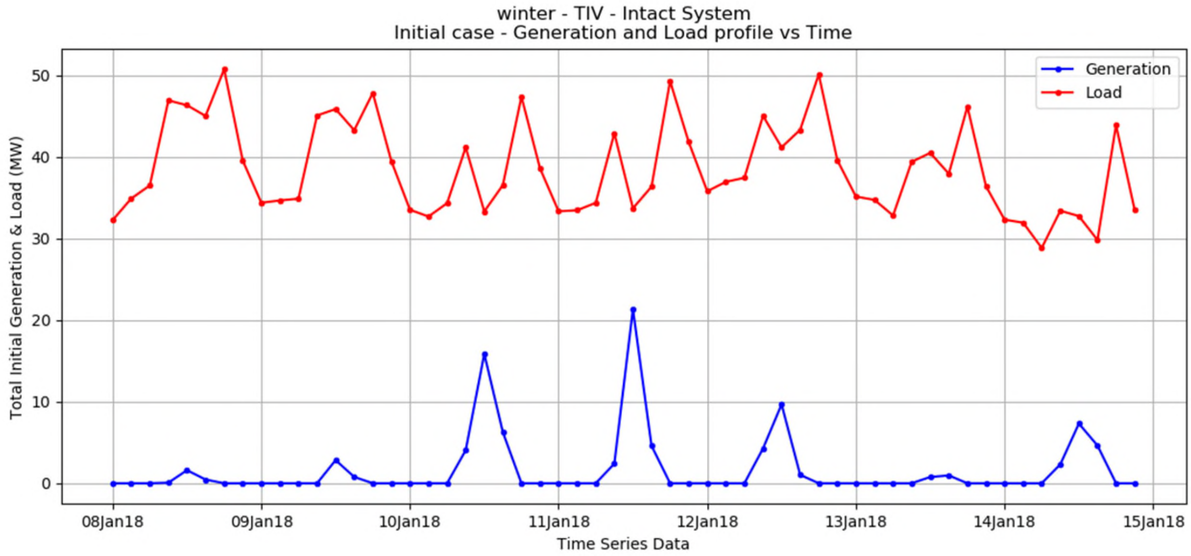
E.1.2. Intact System Summer Week

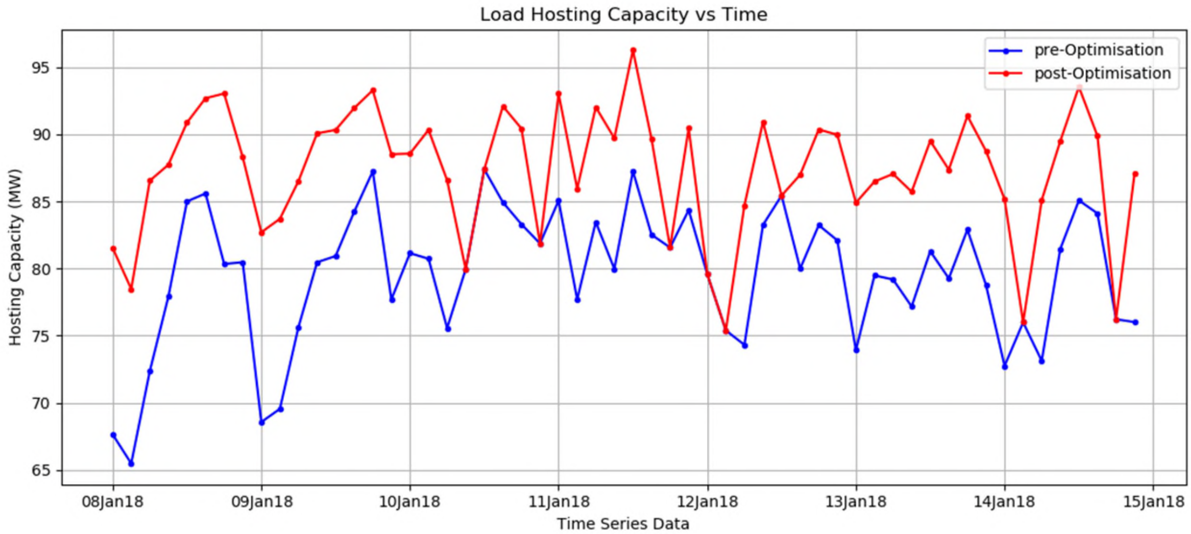


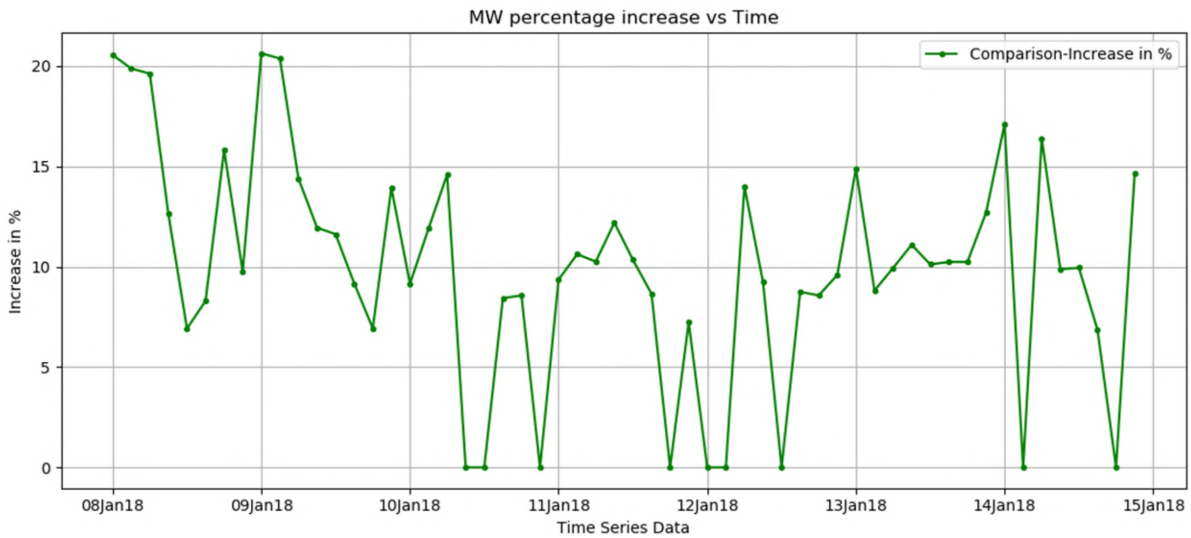
E.1.3. Intact System Autumn Week



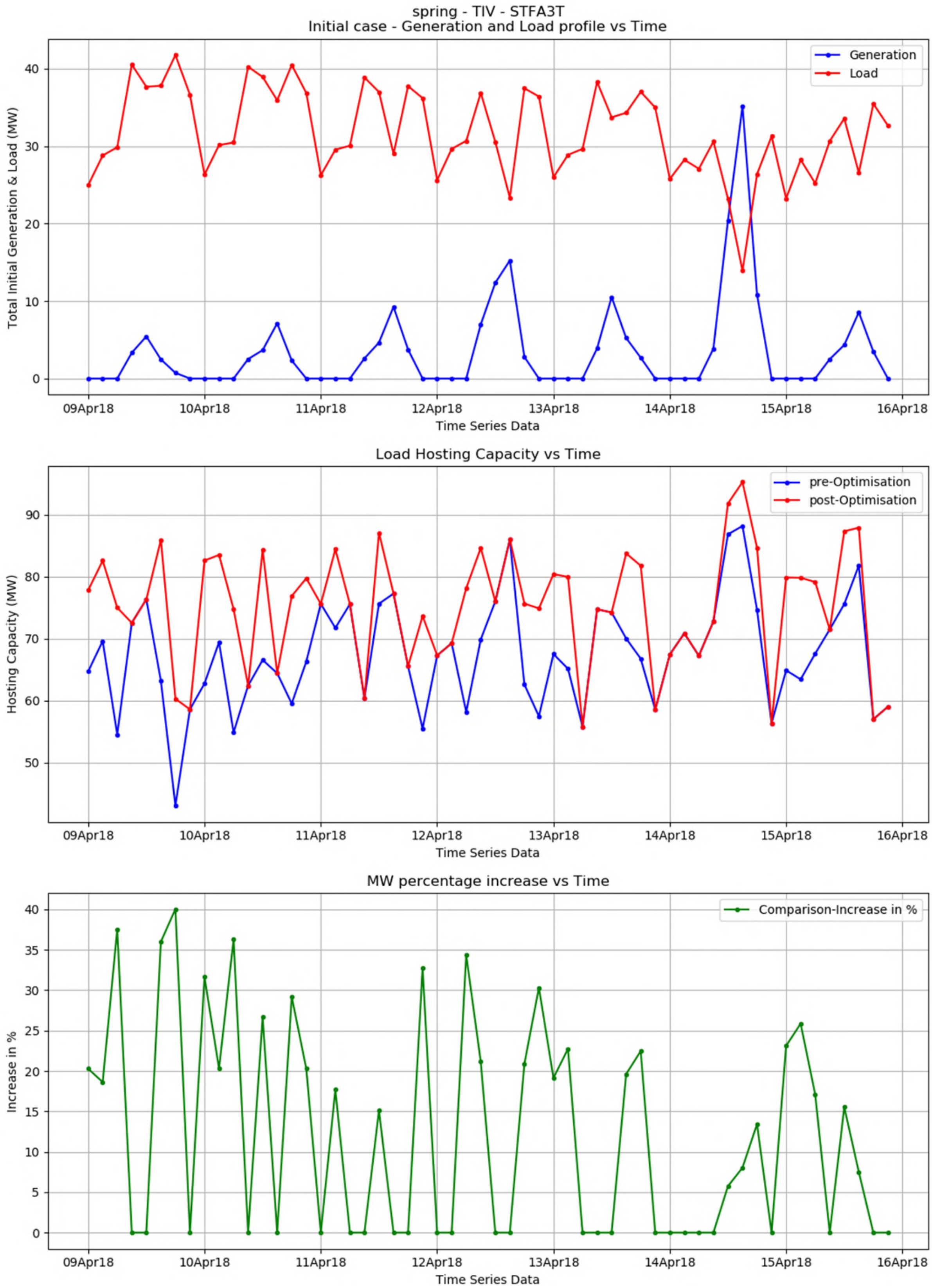
E.1.4. Intact System Winter Week



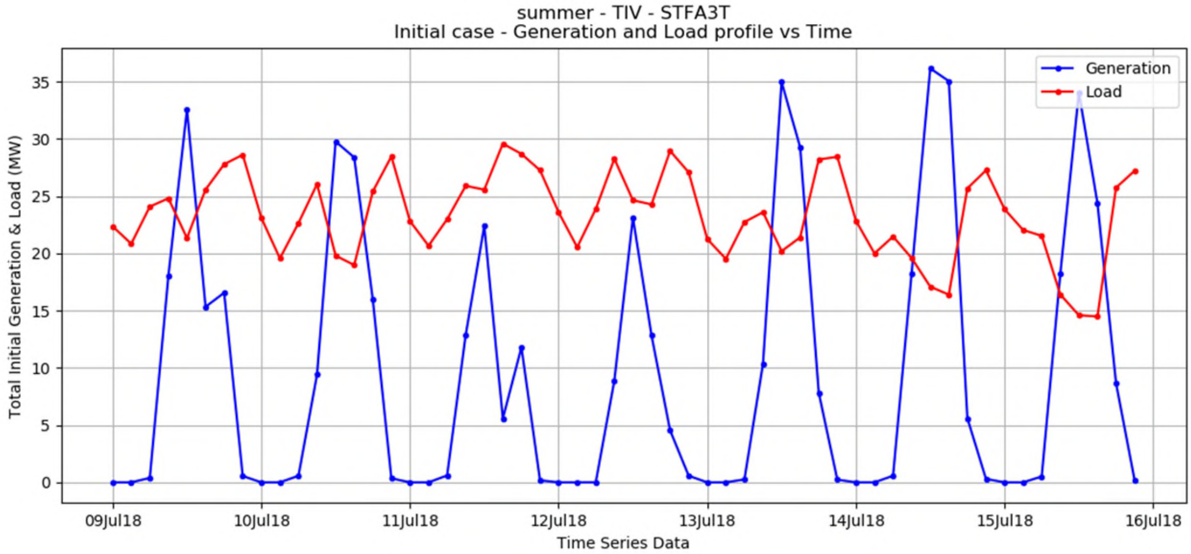


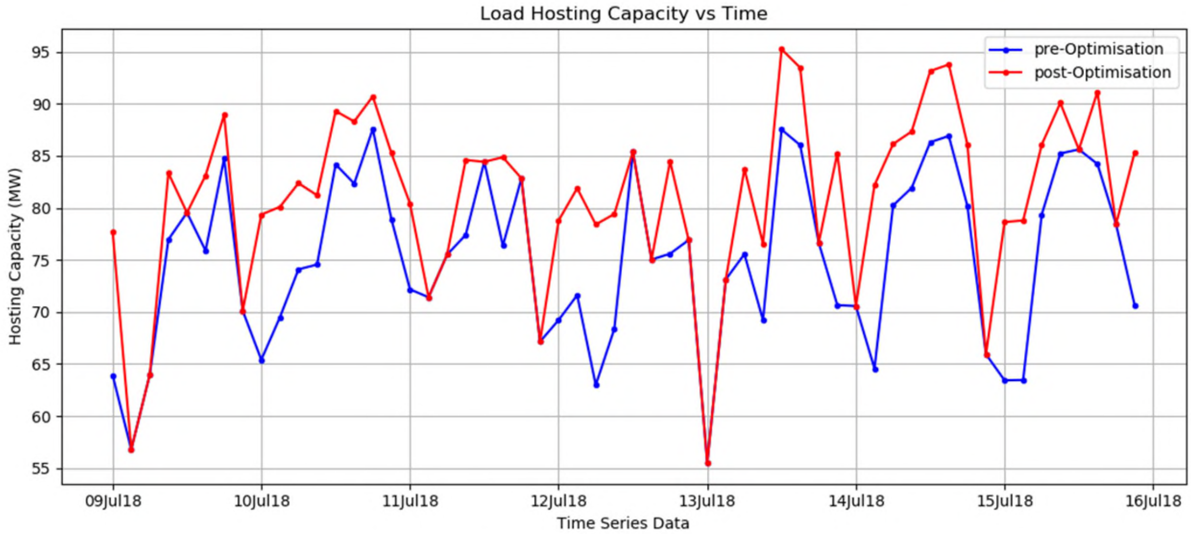


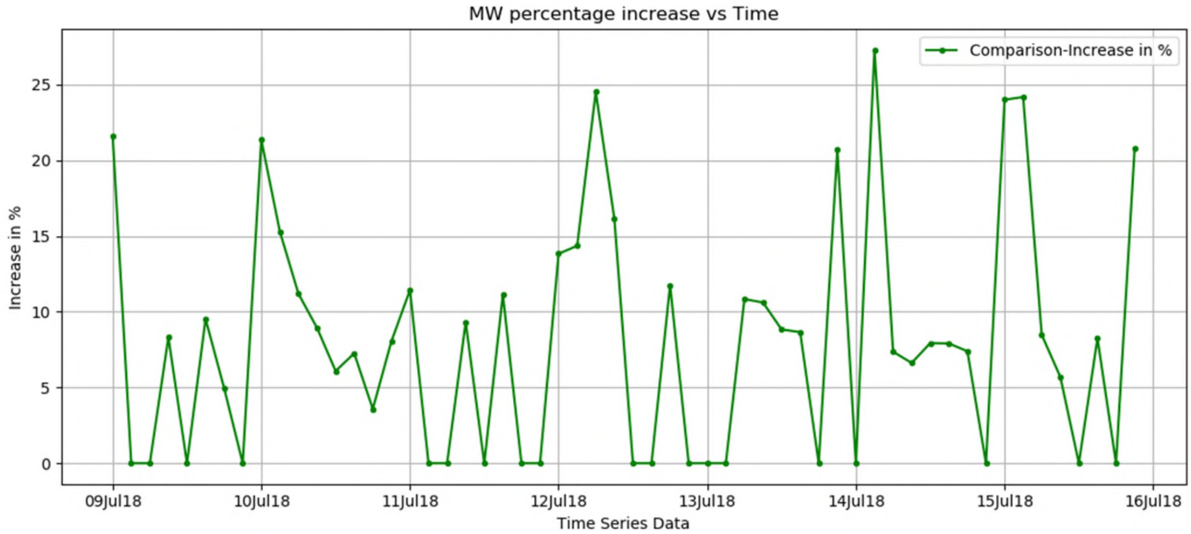
E.1.5. Worst Contingency CULL3K_STFA3T_L1+TIVE3_STFA3T_L1+STFA3_STFA3T_L1 Spring Week



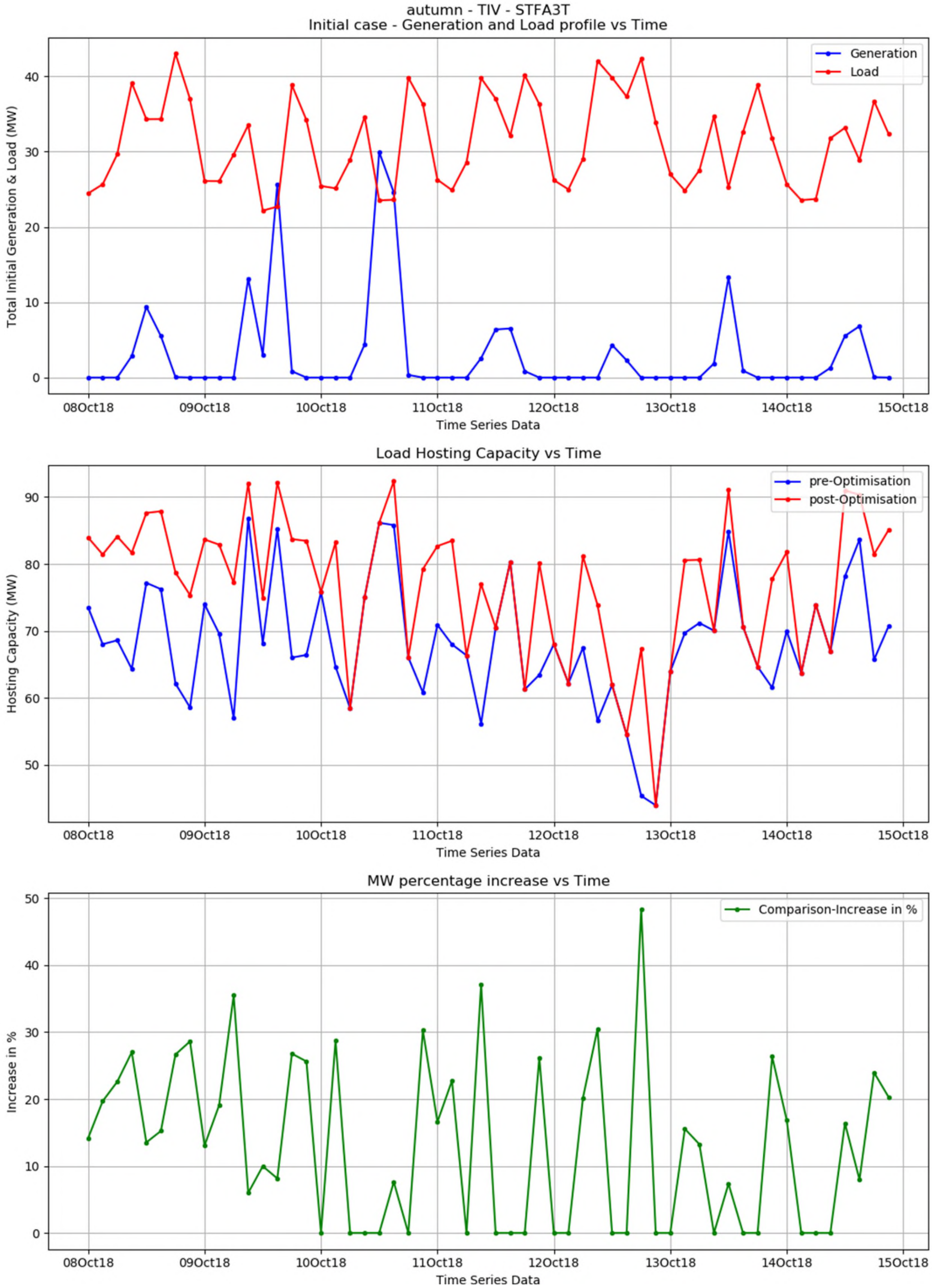
E.1.6. Worst Contingency CULL3K_STFA3T_L1+TIVE3_STFA3T_L1+STFA3_STFA3T_L1 Summer Week



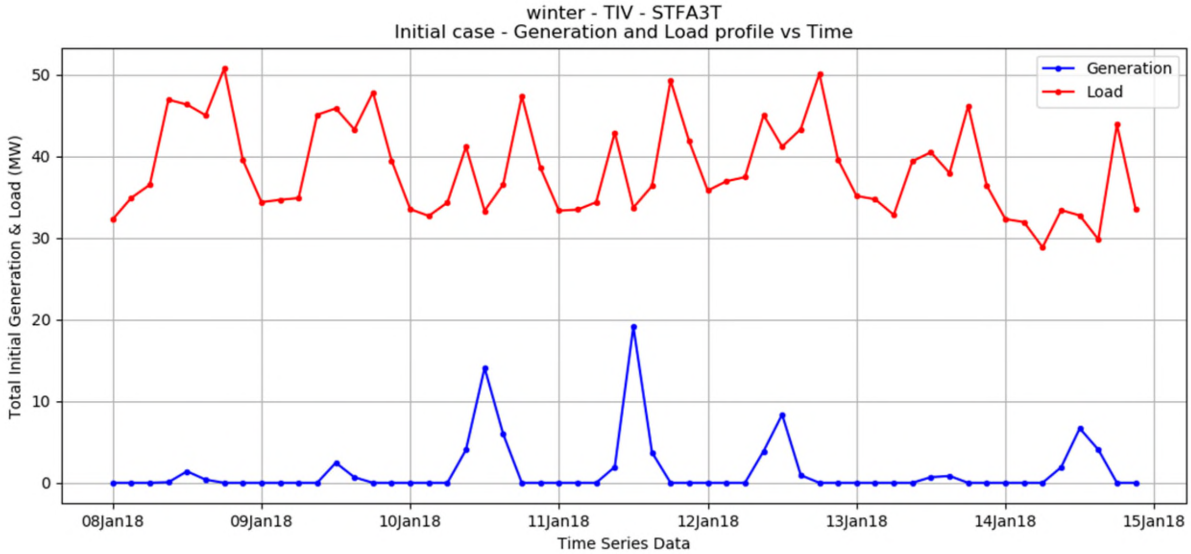


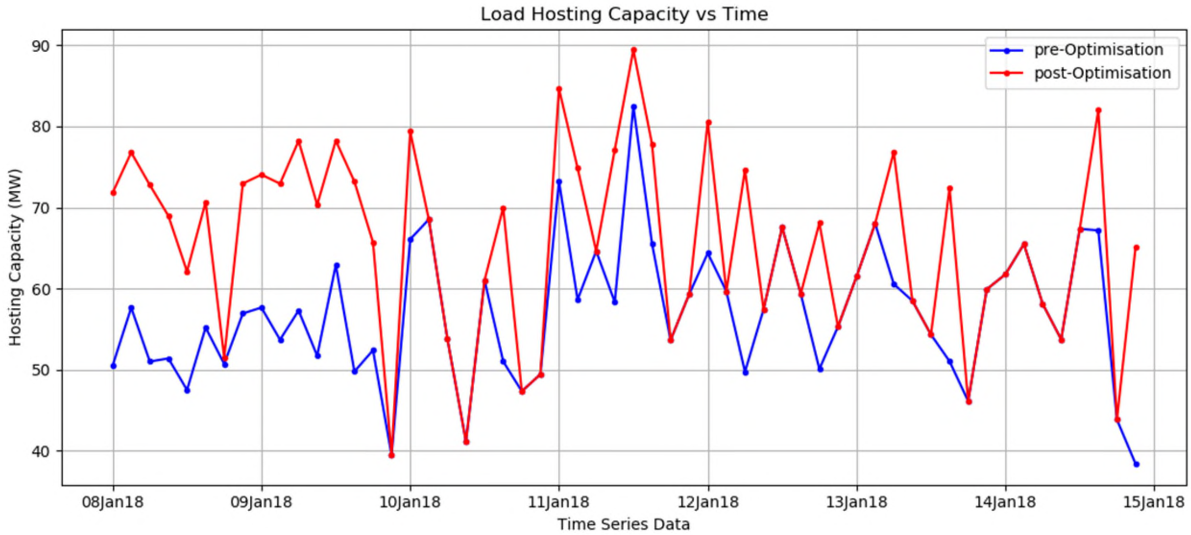


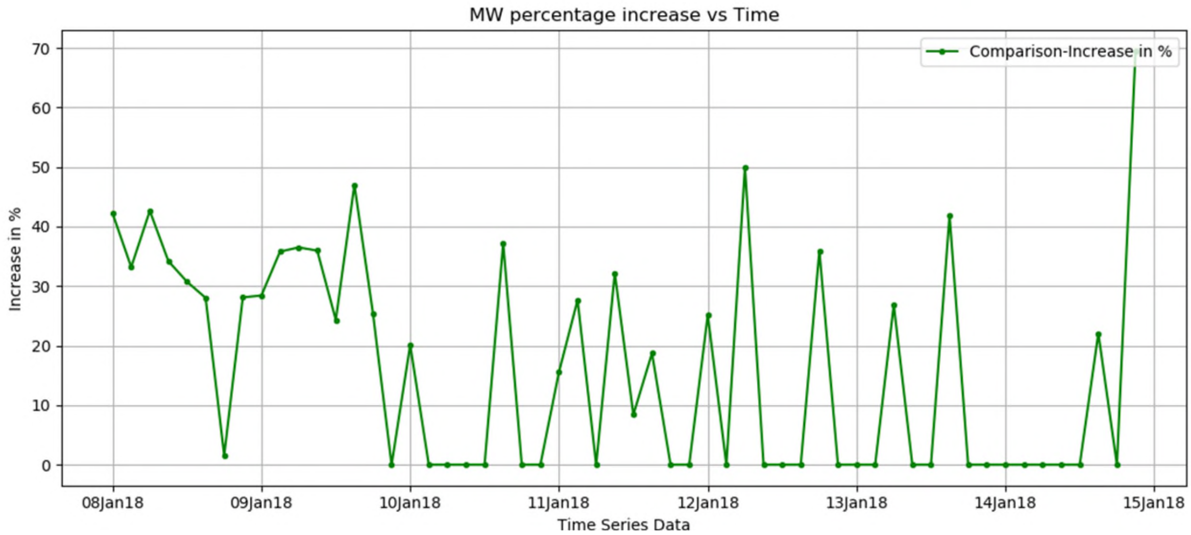
E.1.7. Worst Contingency CULL3K_STFA3T_L1+TIVE3_STFA3T_L1+STFA3_STFA3T_L1 Autumn Week



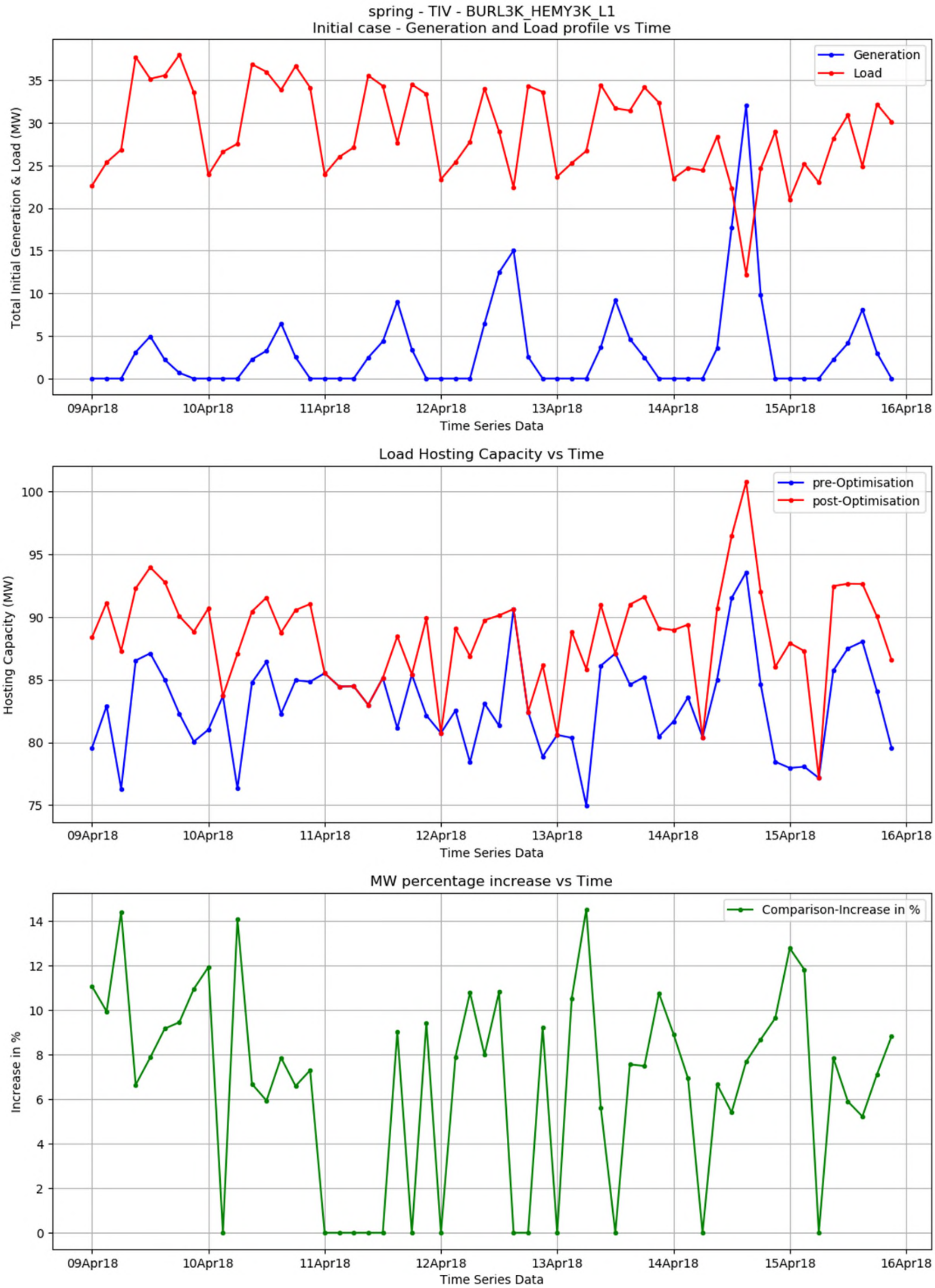
E.1.8. Worst Contingency CULL3K_STFA3T_L1+TIVE3_STFA3T_L1+STFA3_STFA3T_L1 Winter Week



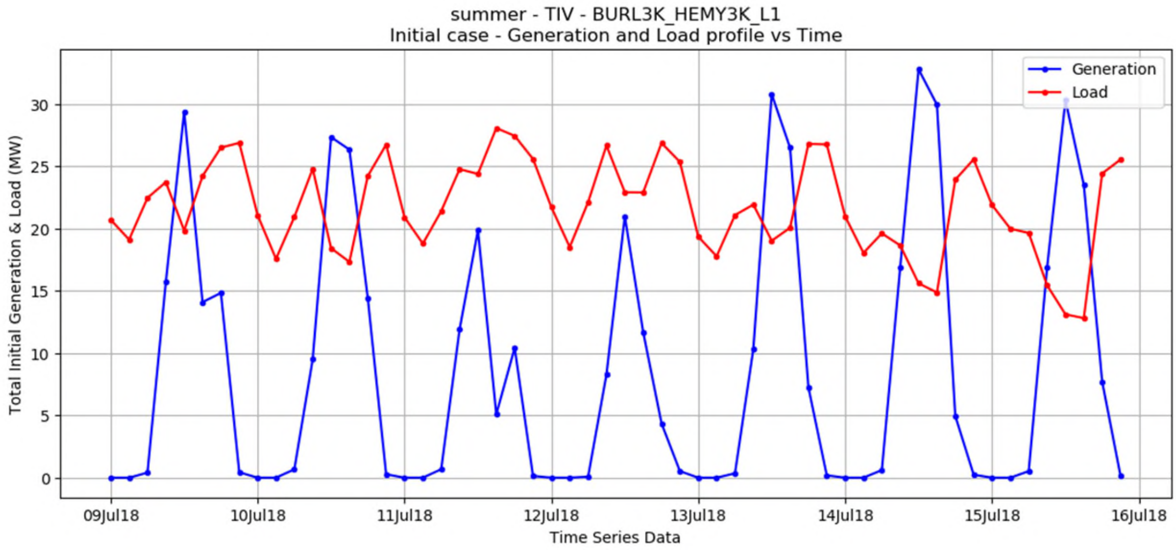


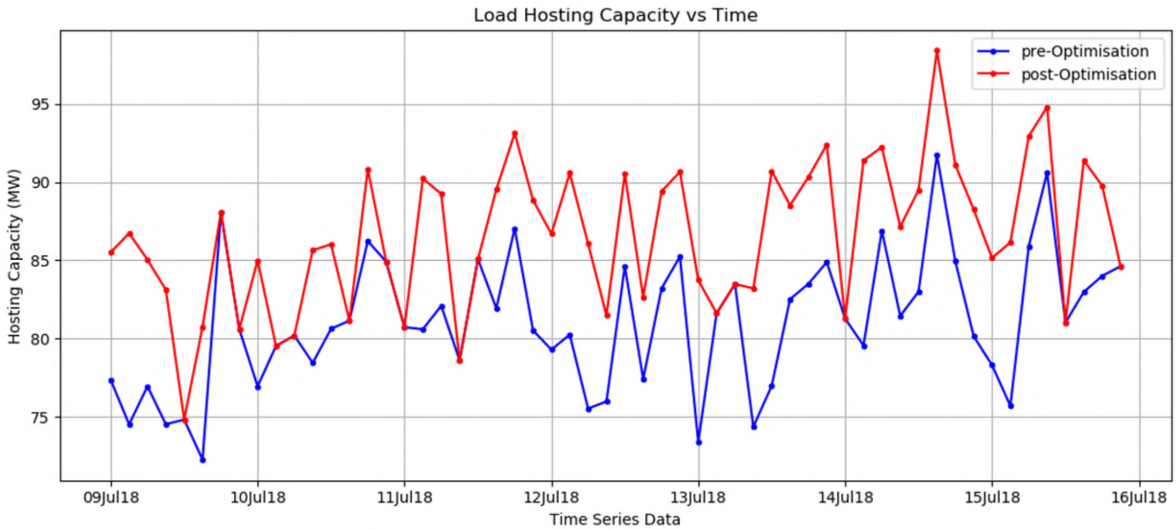


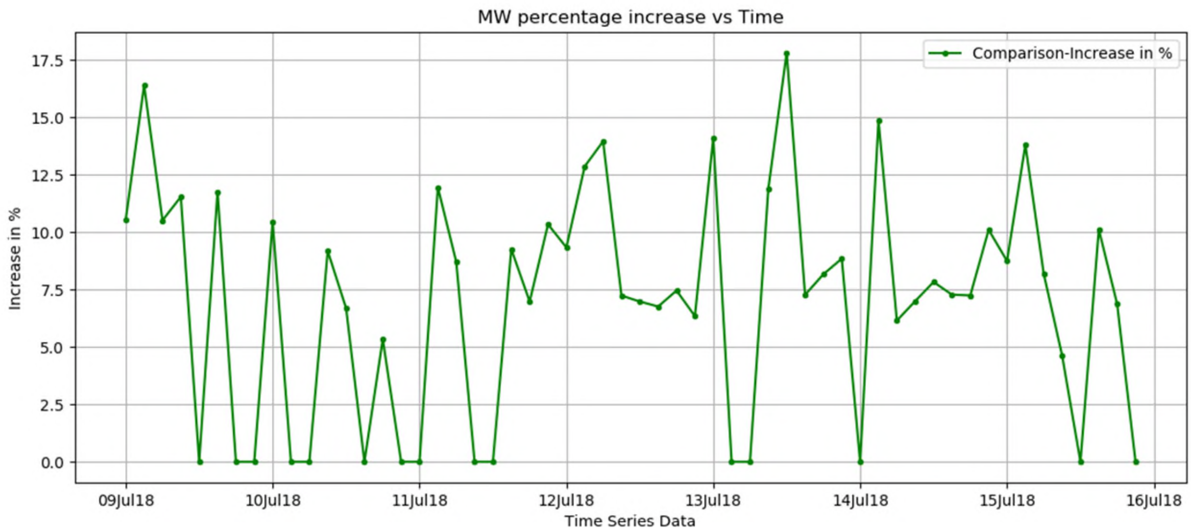
E.1.9. Best Contingency BURL3K_HEMY3K_L1 Spring Week



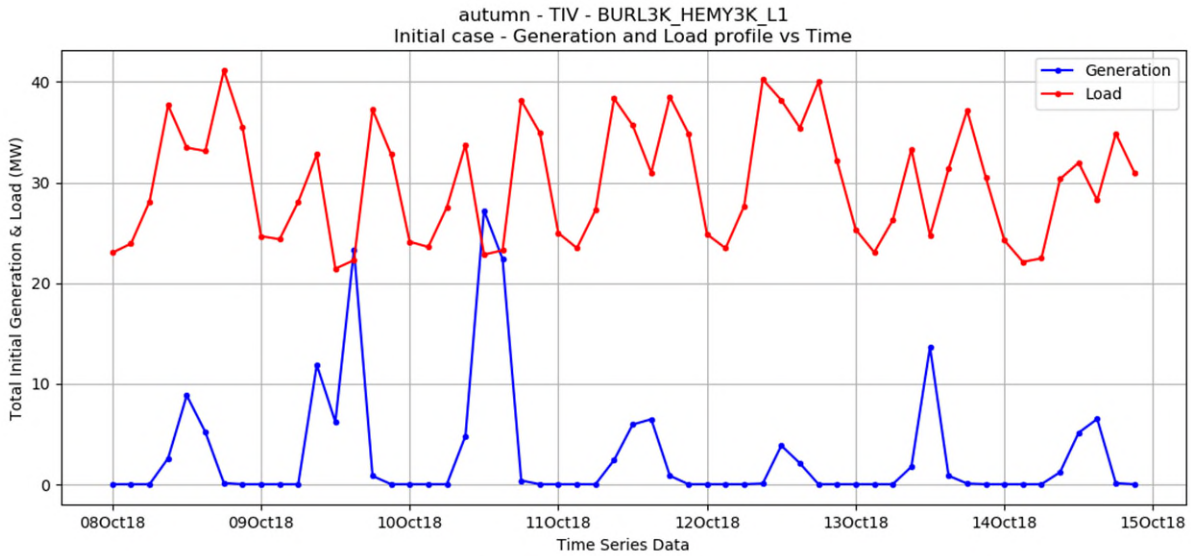
E.1.10. Best Contingency BURL3K_HEMY3K_L1 Summer Week

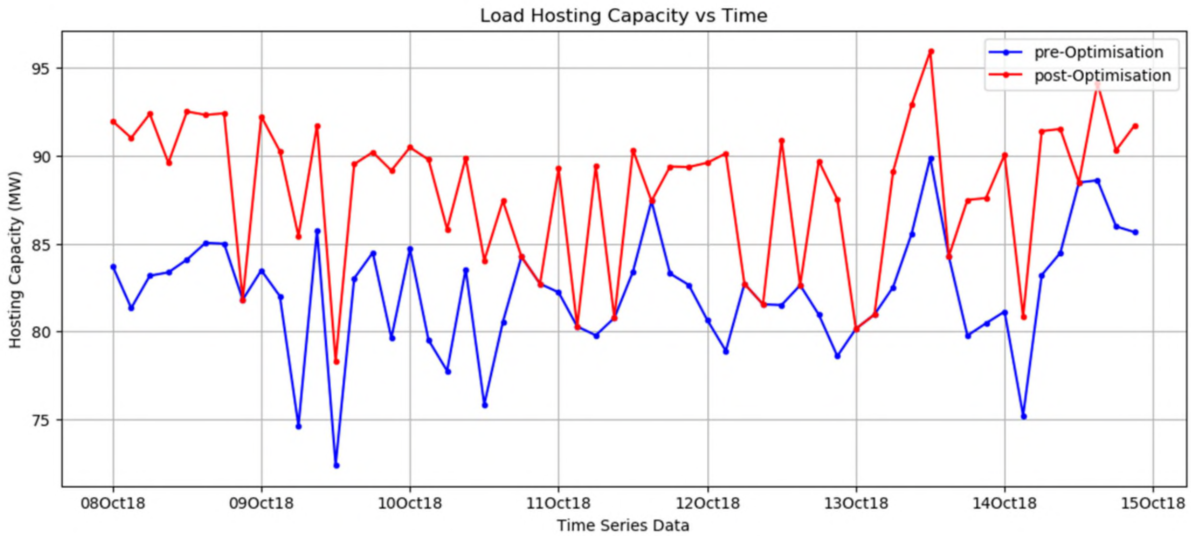


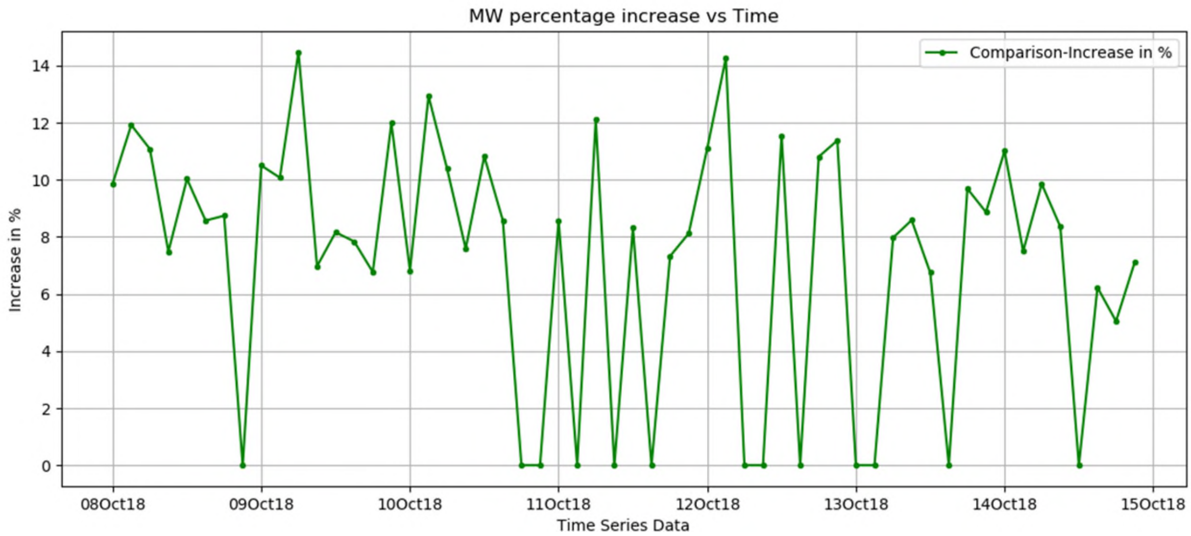




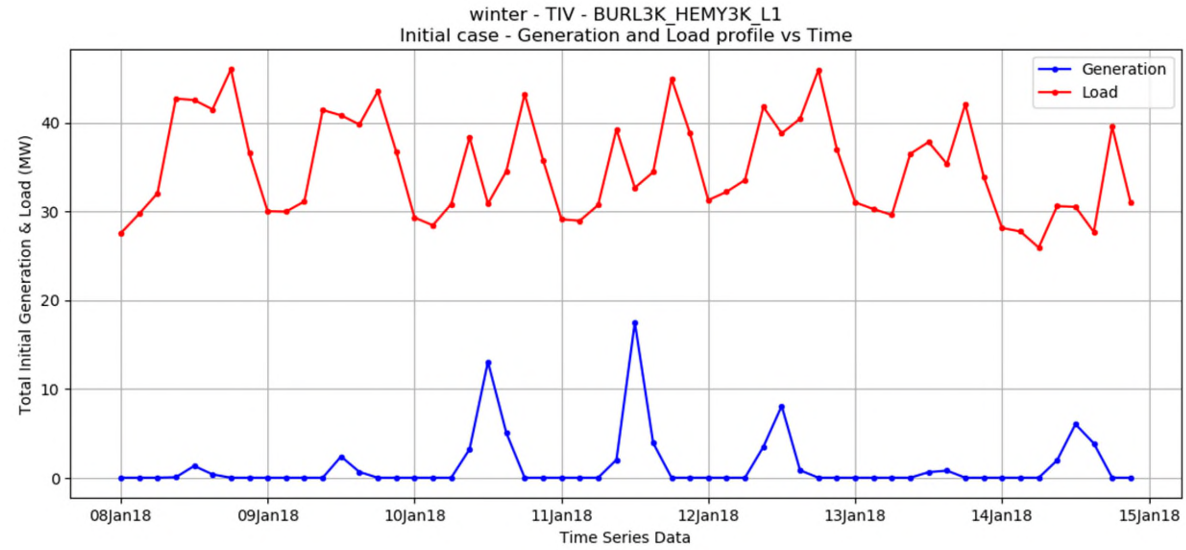
E.1.11. Best Contingency BURL3K_HEMY3K_L1 Autumn Week

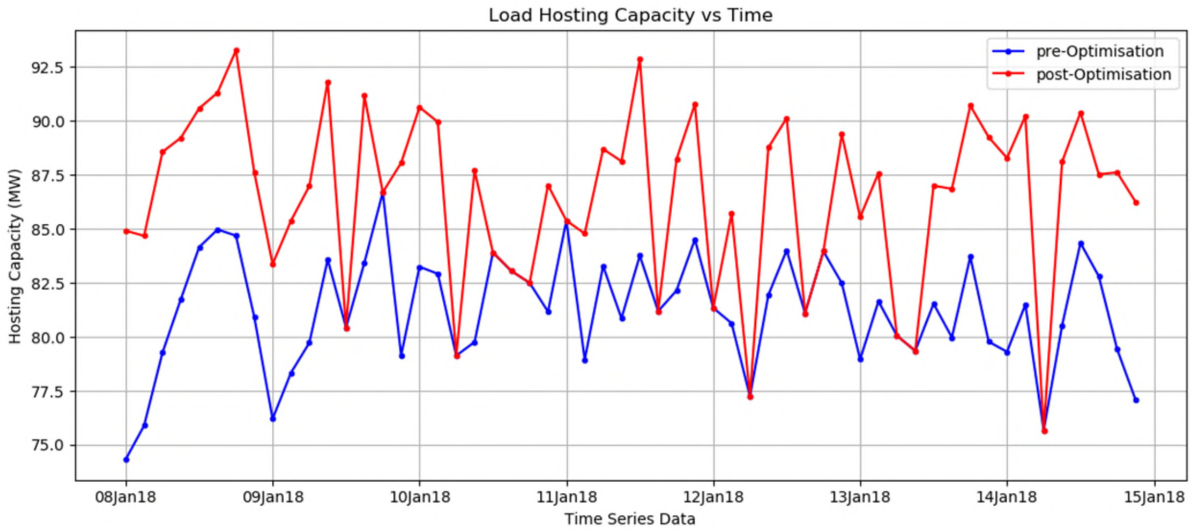


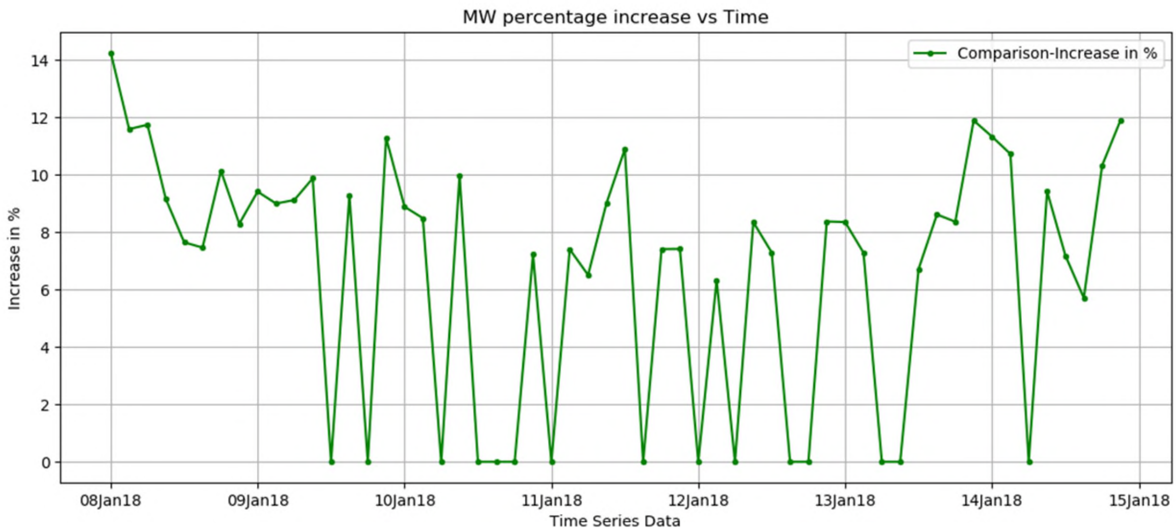




E.1.12. Best Contingency BURL3K_HEMY3K_L1 Winter Week

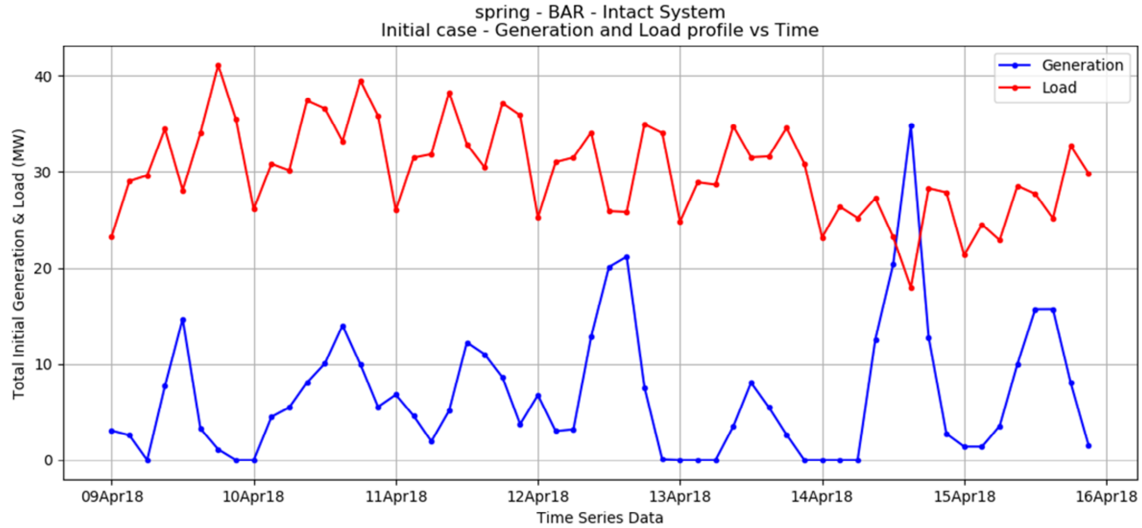


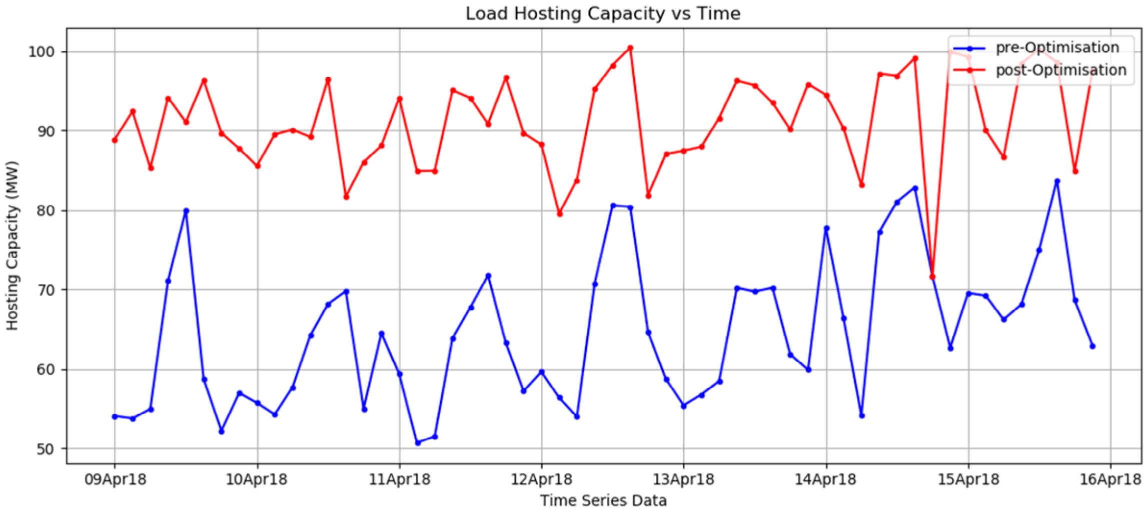


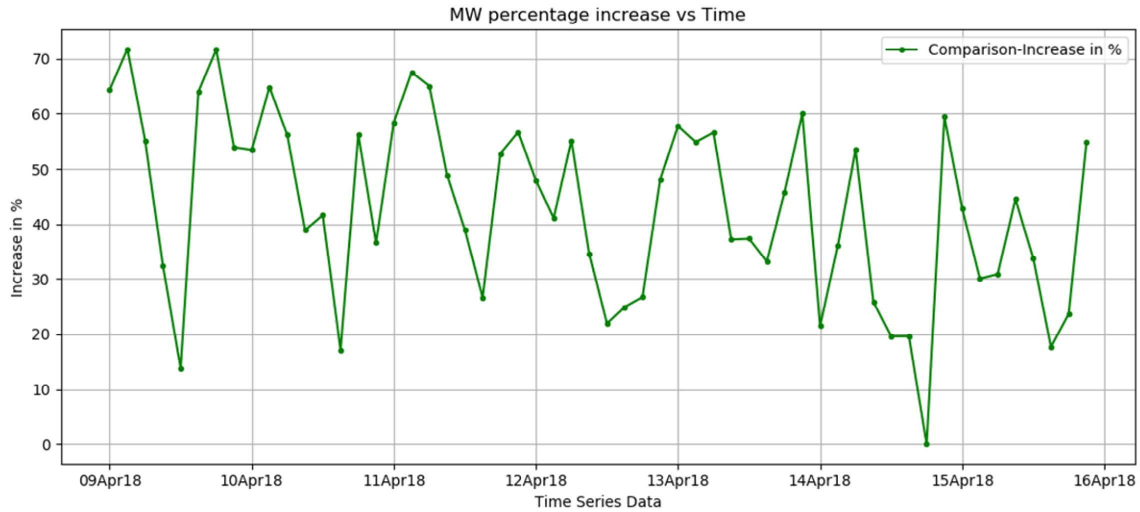


E.2. Barnstaple 33 kV BSP

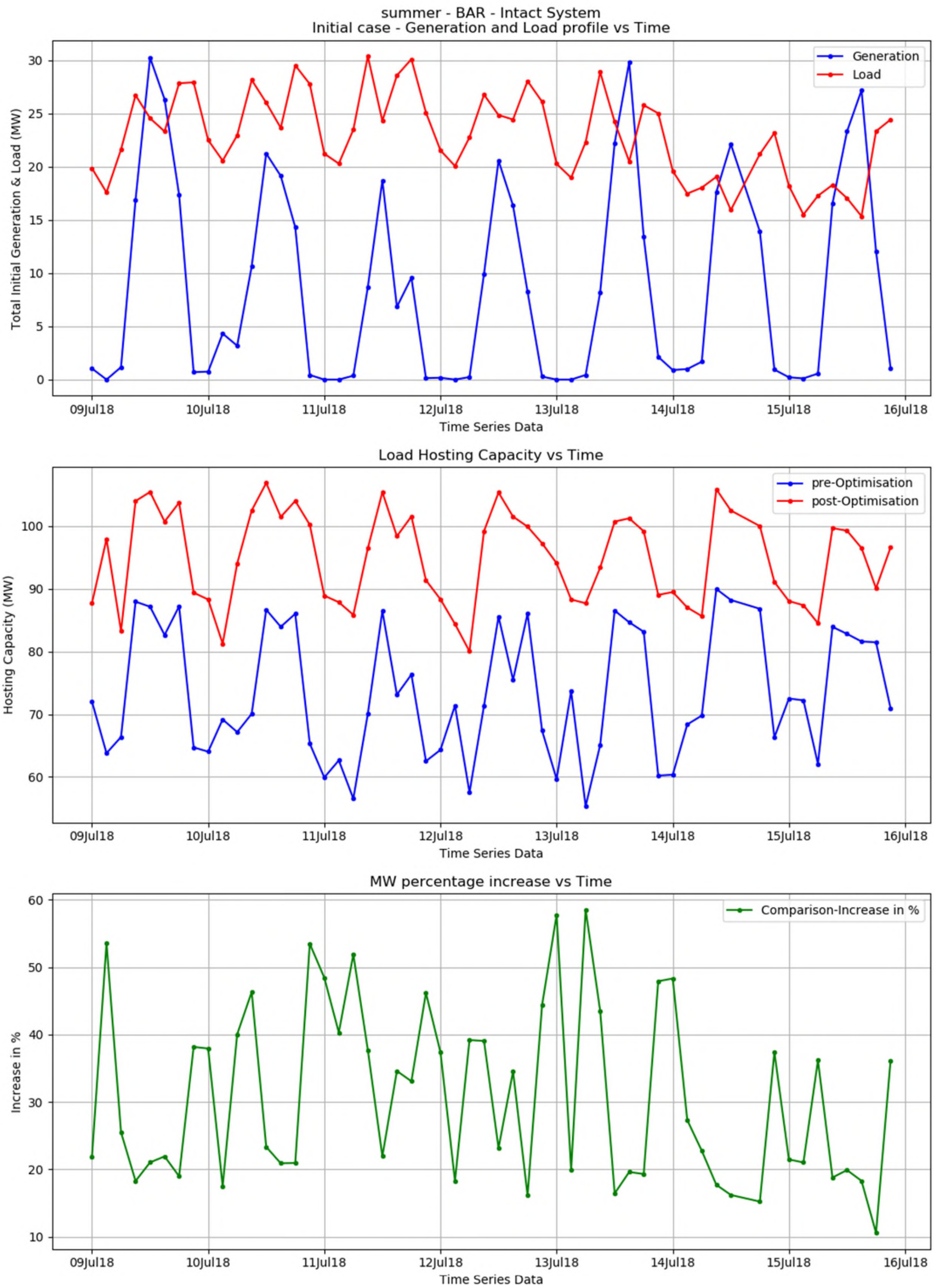
E.2.1. Intact System Spring Week



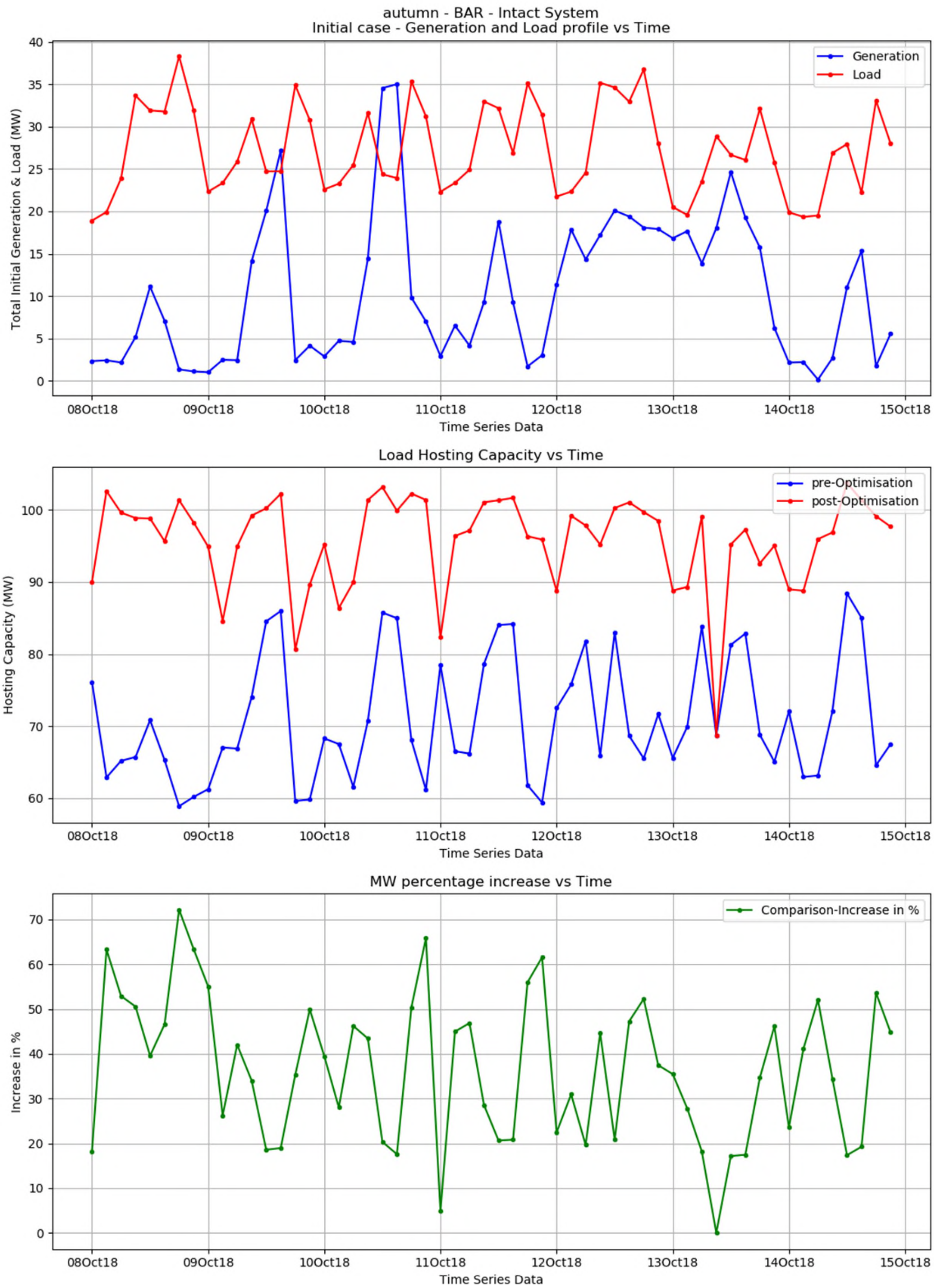




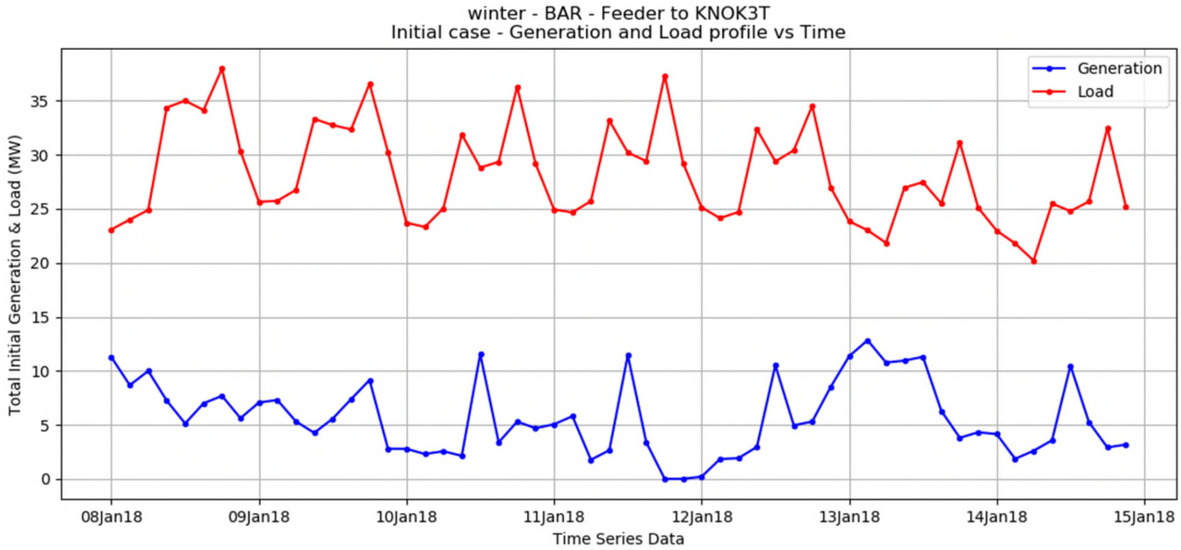
E.2.2. Intact System Summer Week

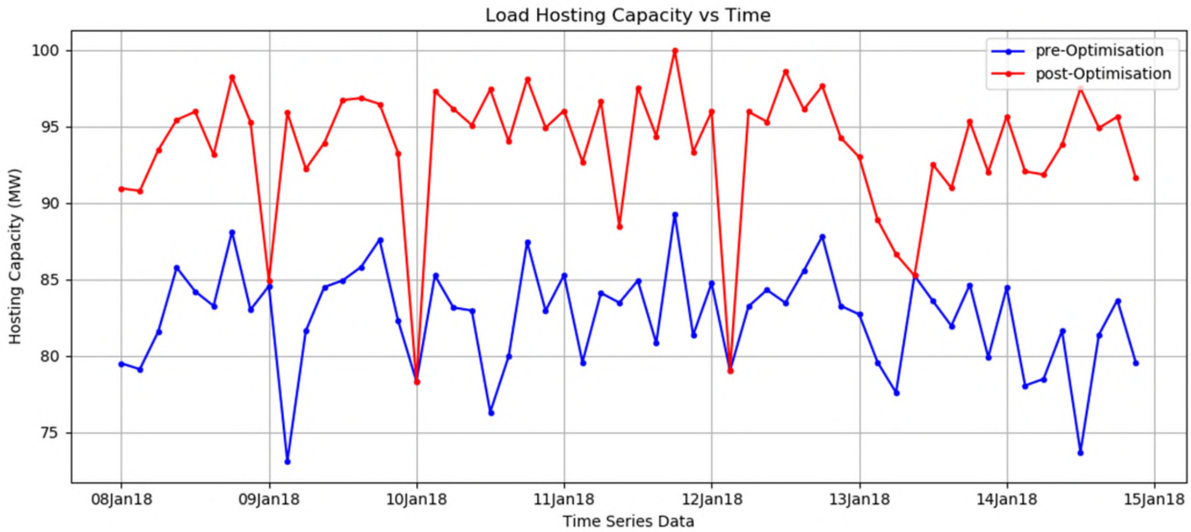


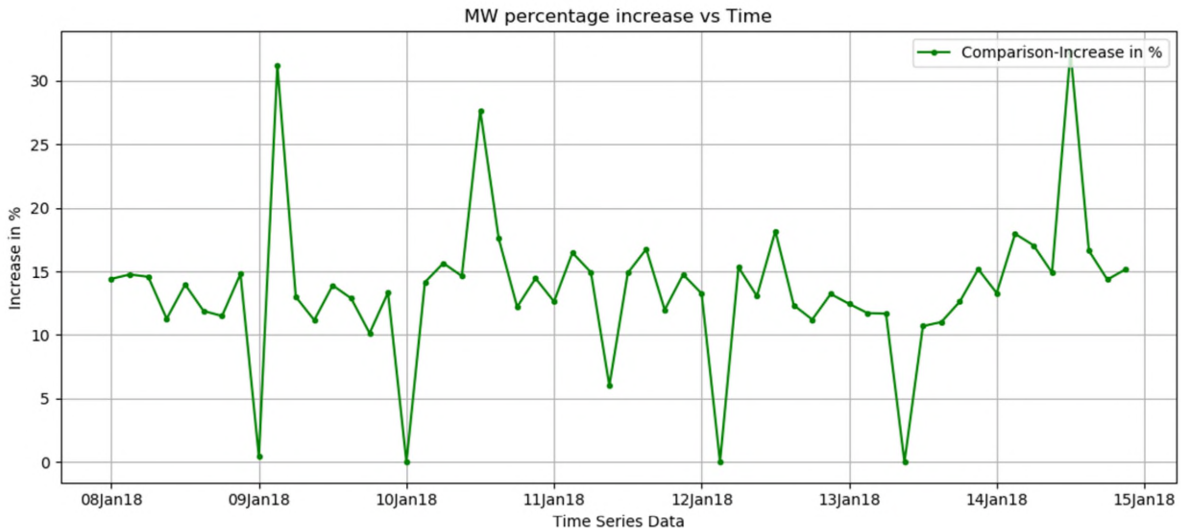
E.2.3. Intact System Autumn Week



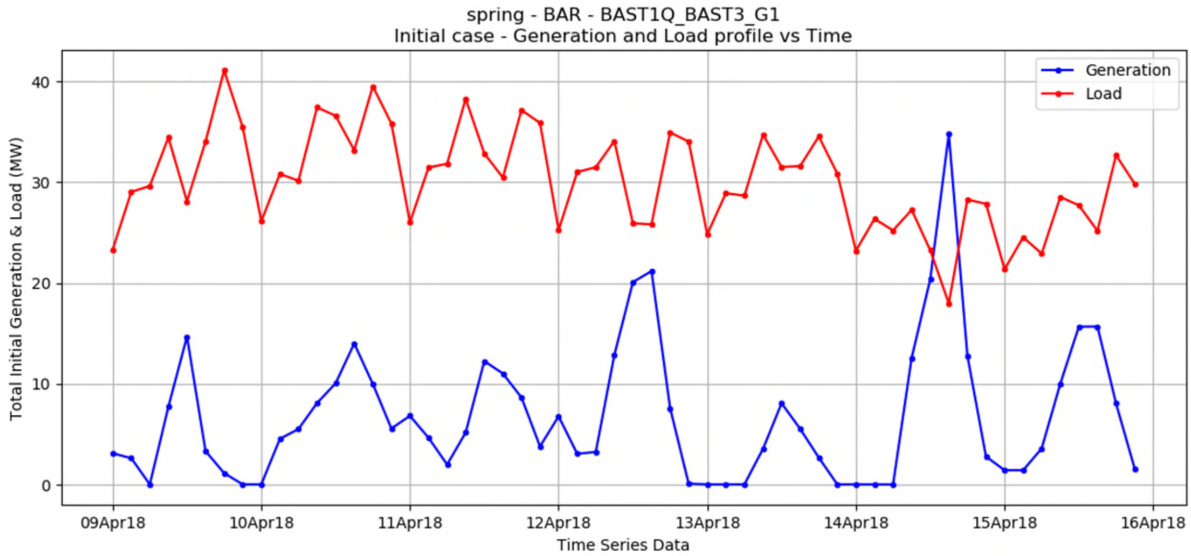
E.2.4. Intact System Winter Week

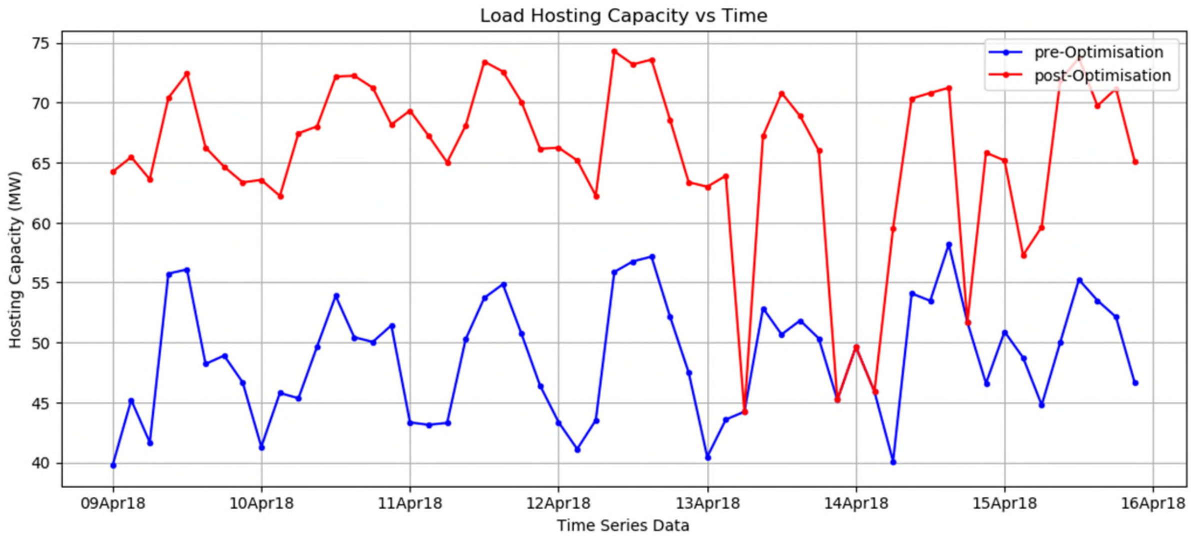


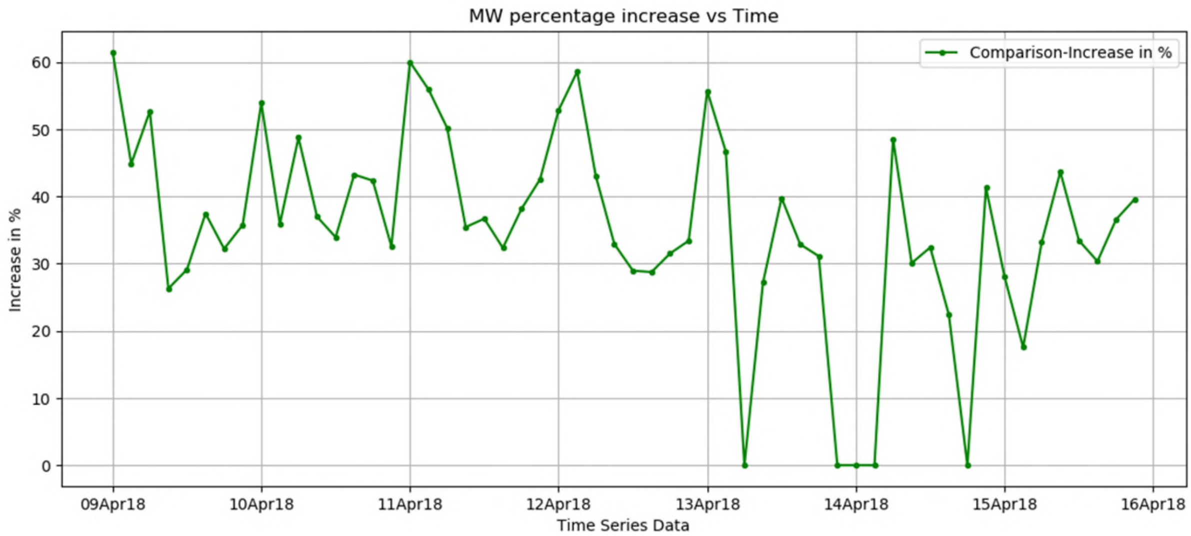




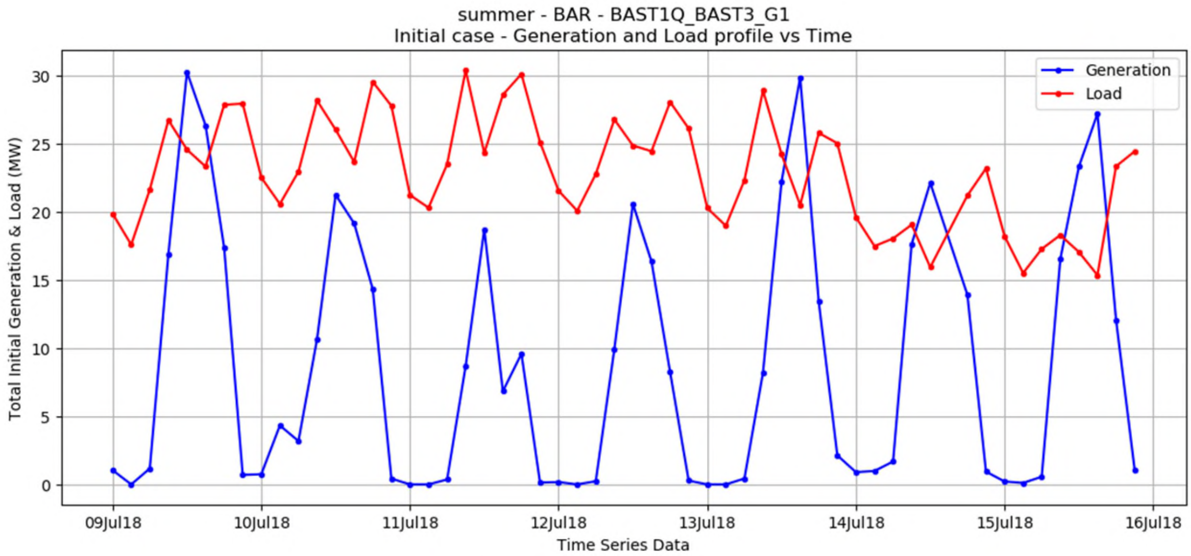
E.2.5. Worst Contingency BAST1Q_BAST3_G1 Spring Week

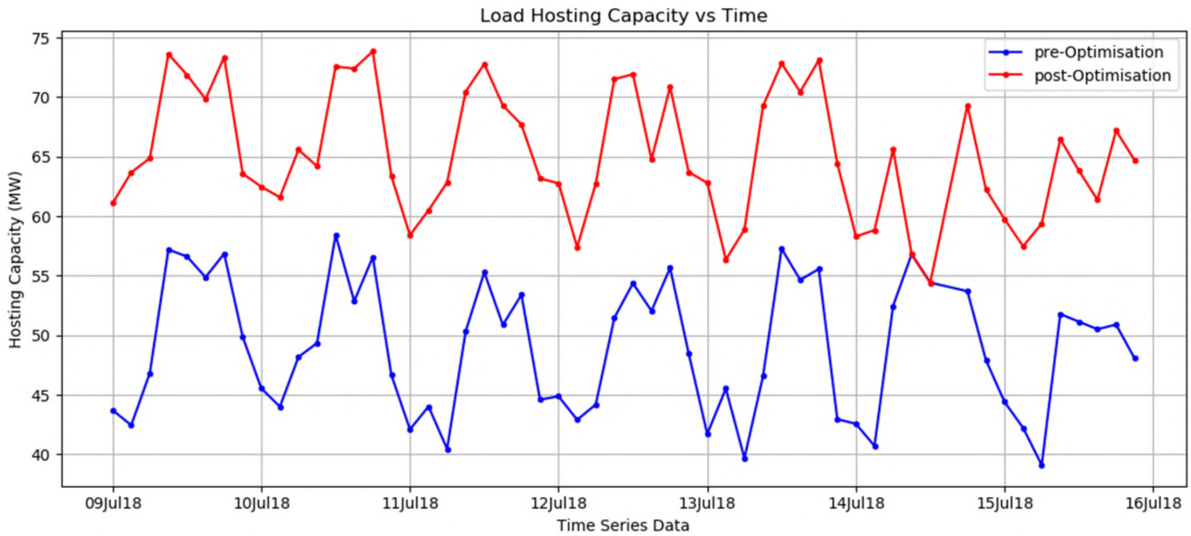


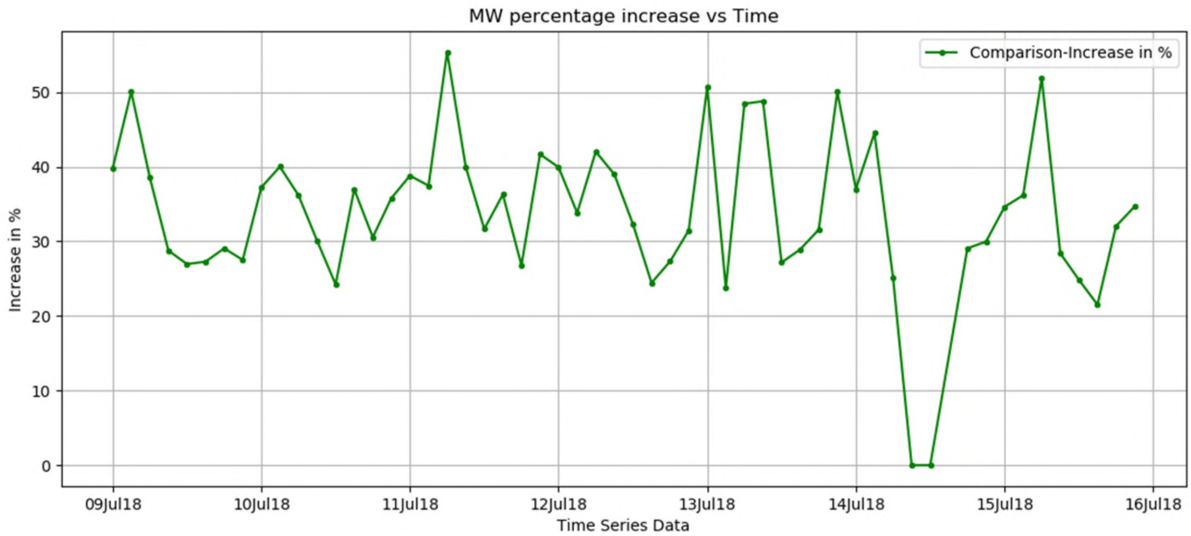




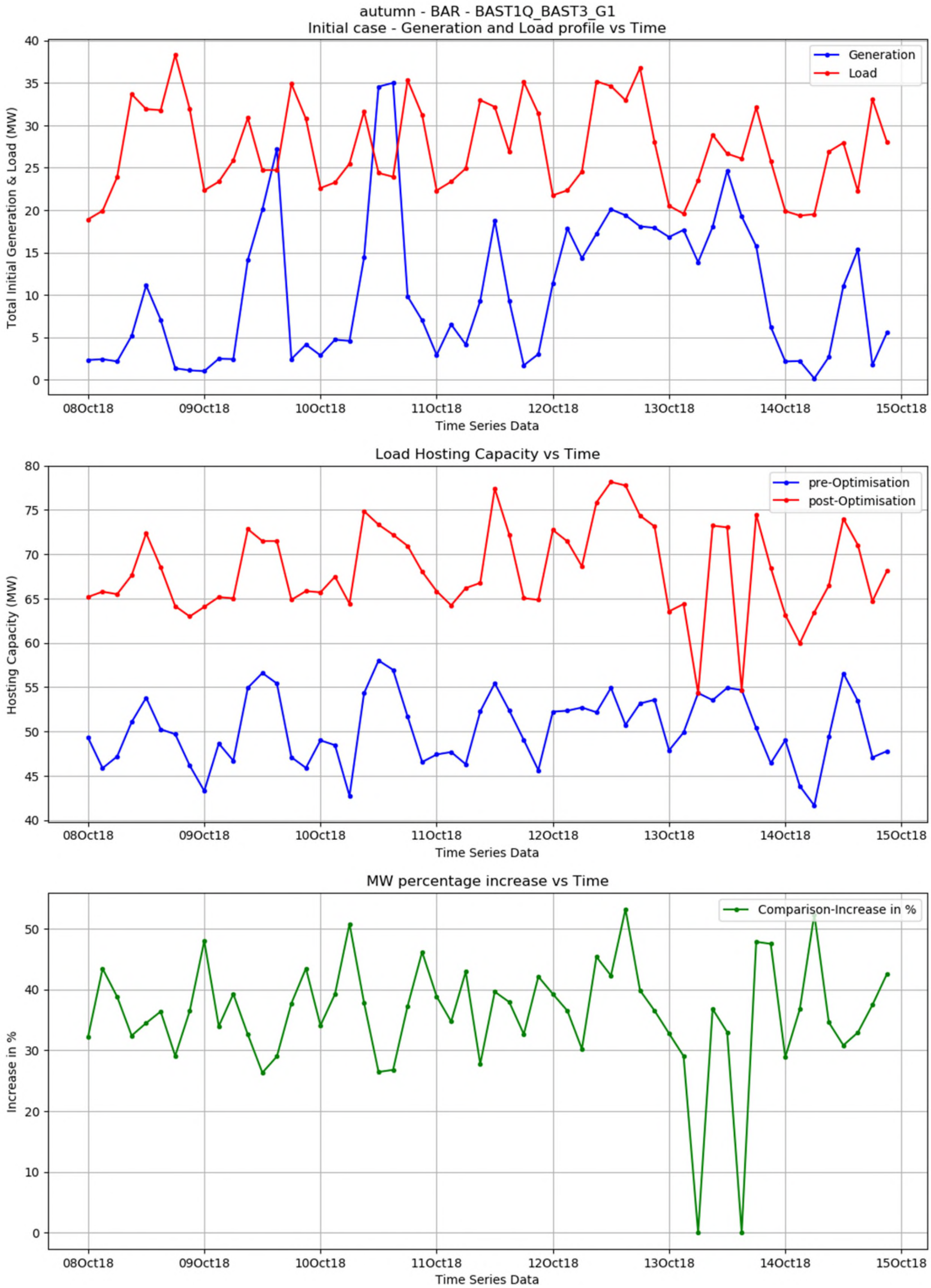
E.2.6. Worst Contingency BAST1Q_BAST3_G1 Summer Week



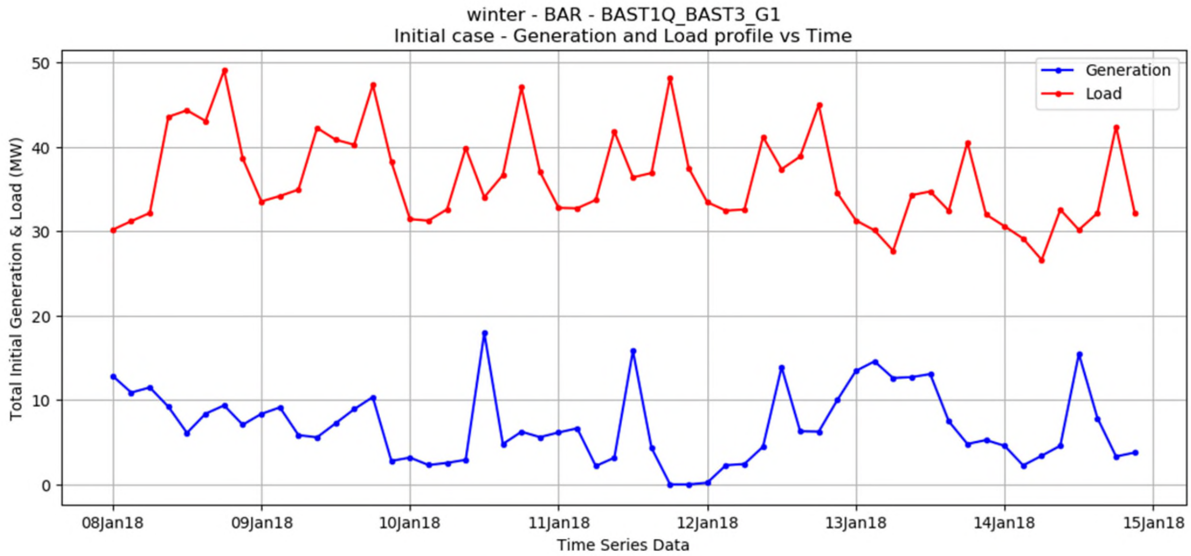


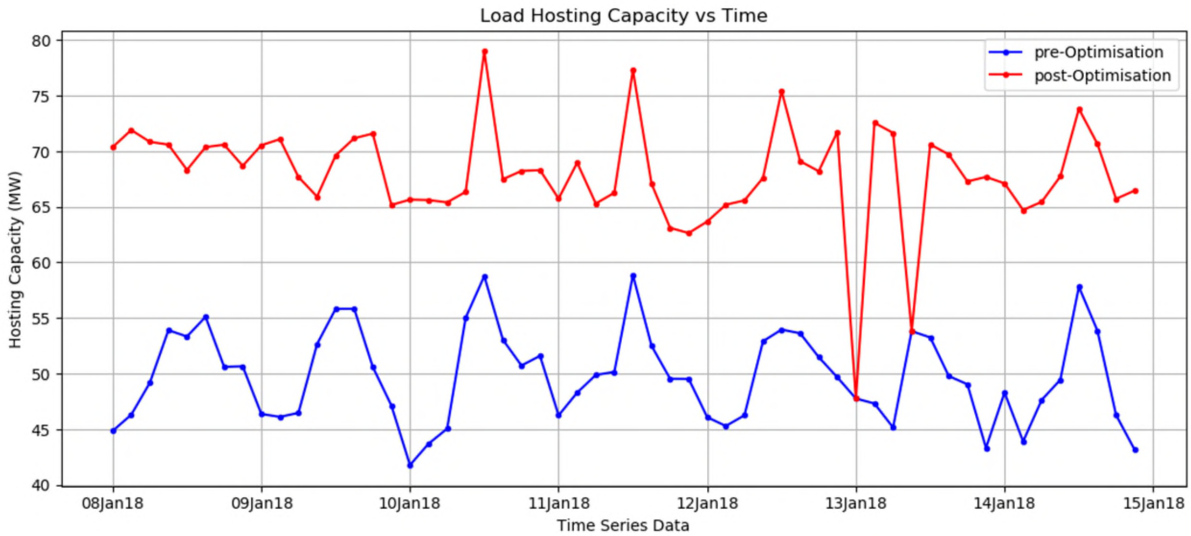


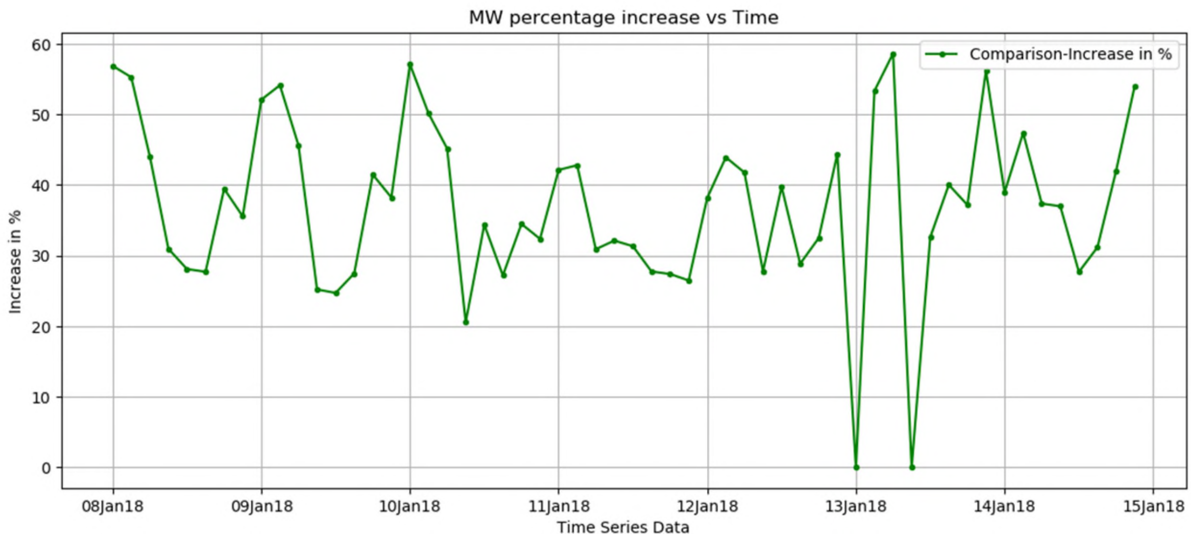
E.2.7. Worst Contingency BAST1Q_BAST3_G1 Autumn Week



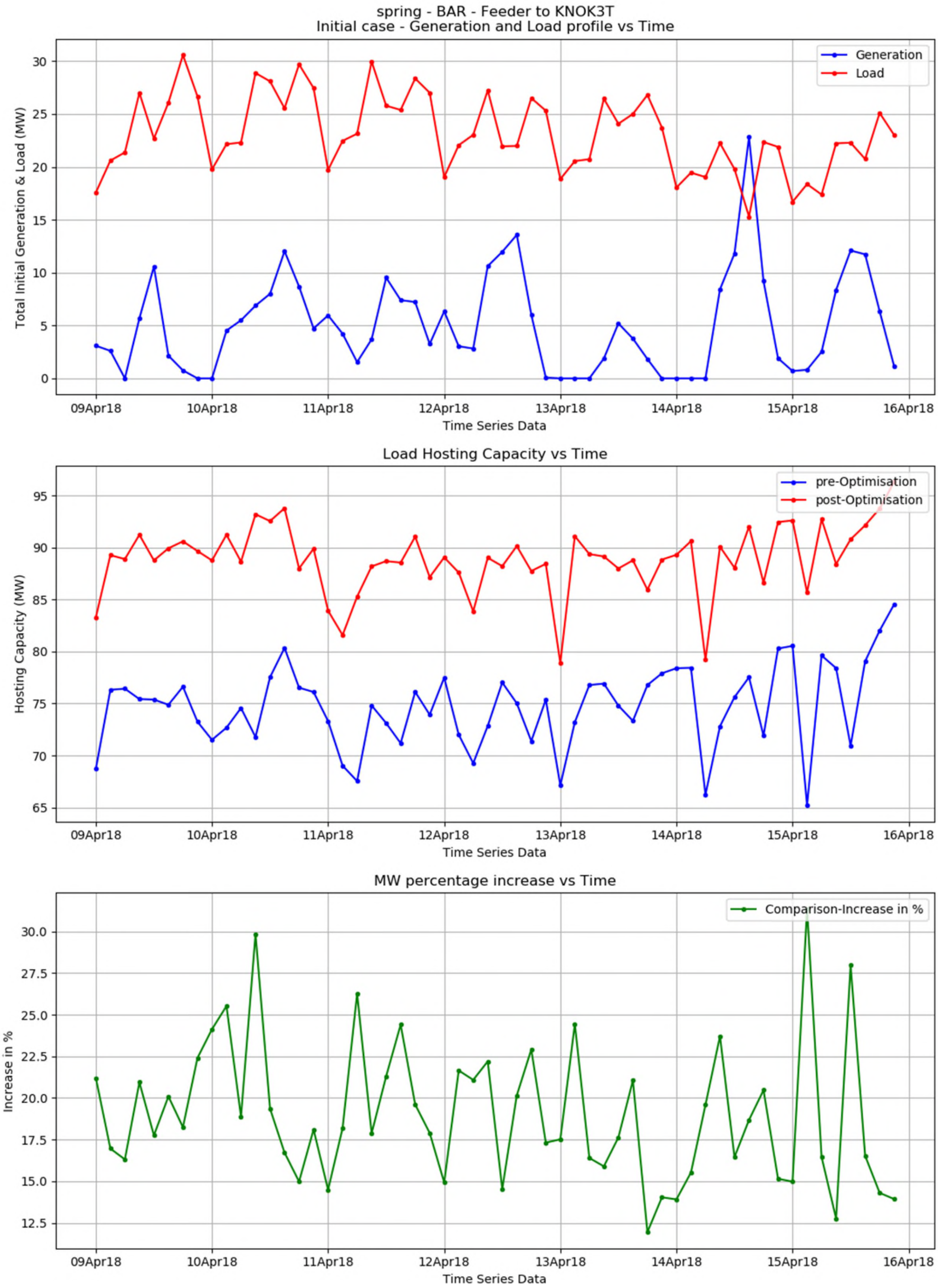
E.2.8. Worst Contingency BAST1Q_BAST3_G1 Winter Week



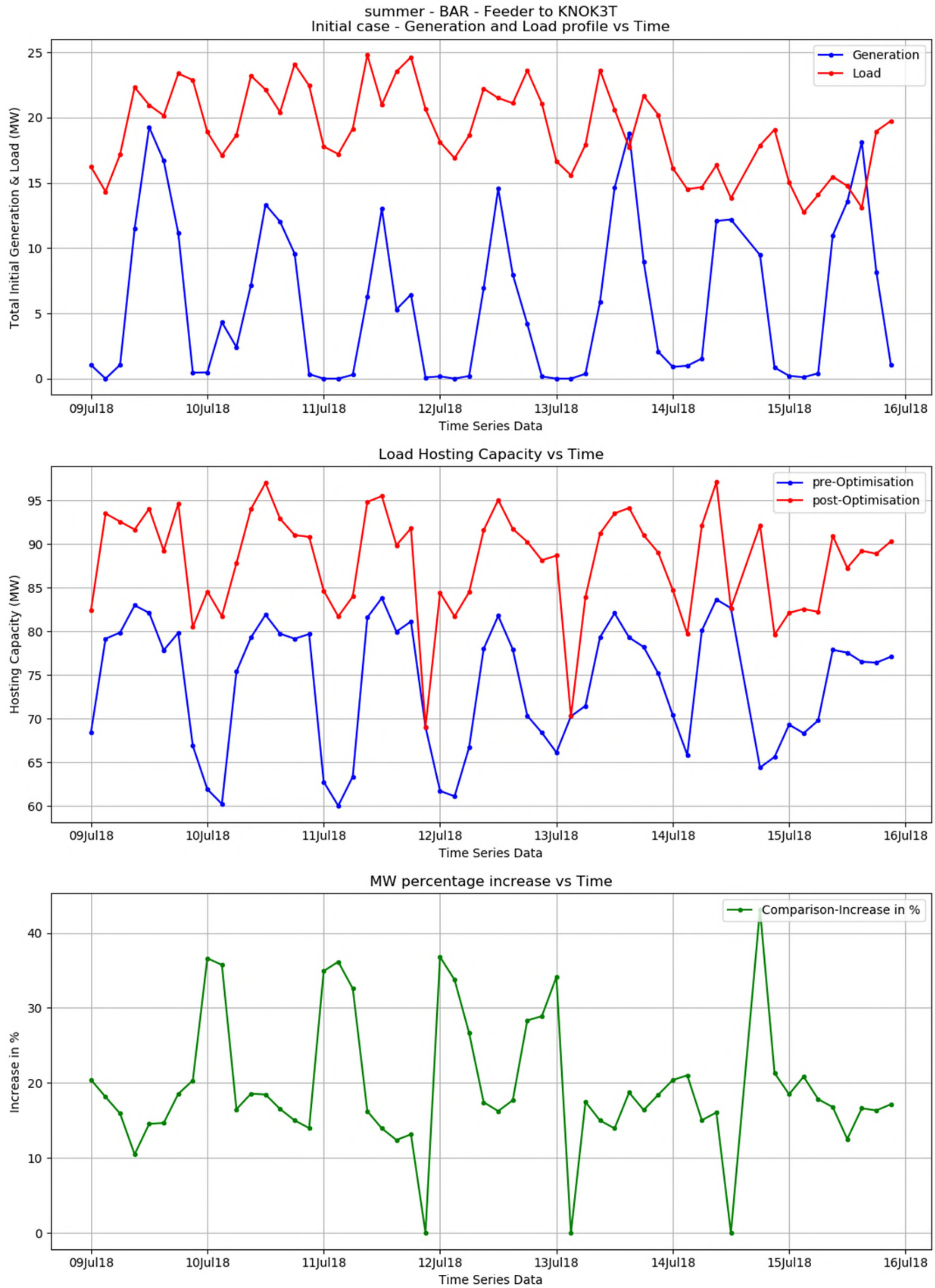




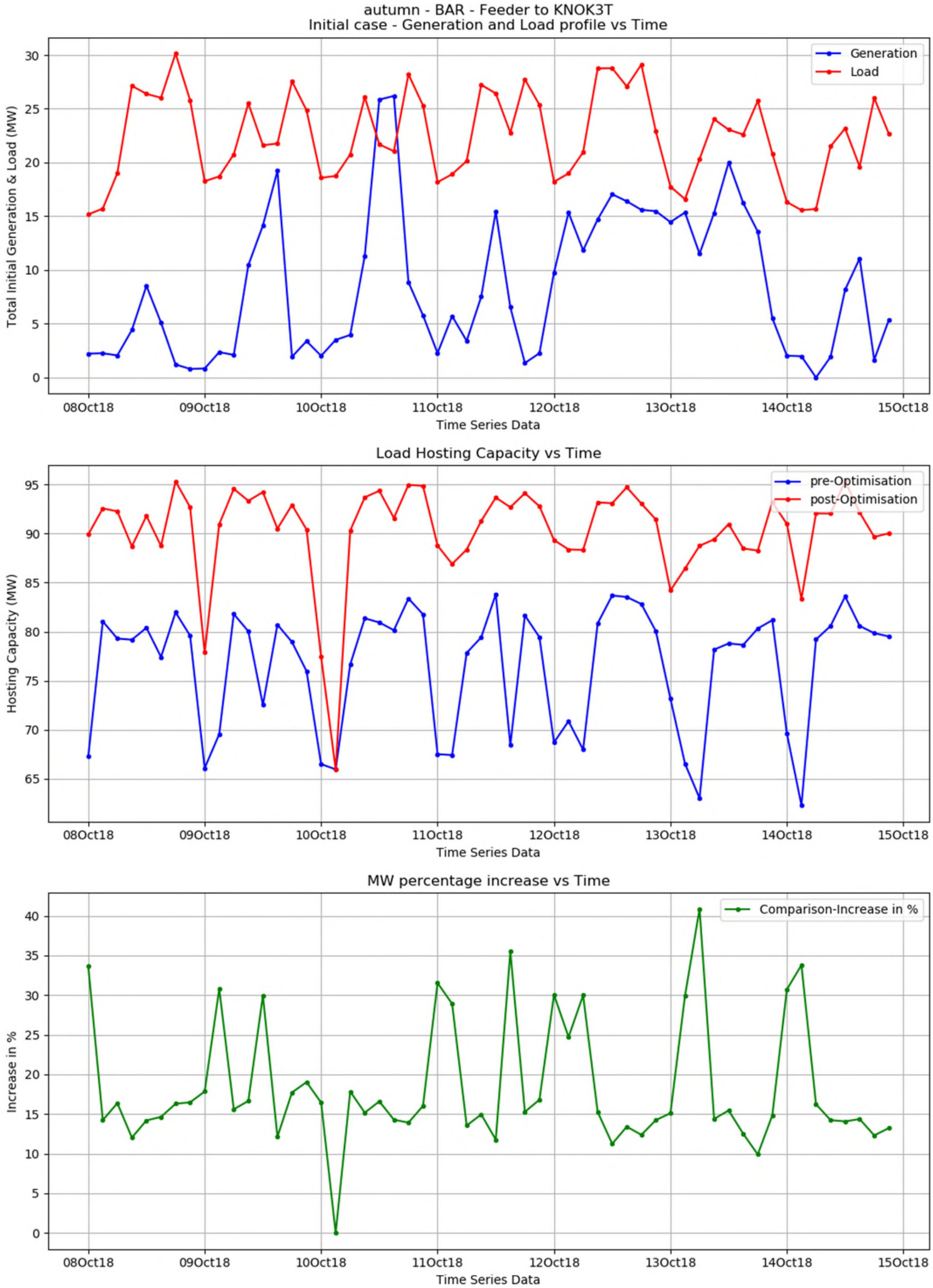
E.2.9. Best Contingency TORR3K_DARM3T_L1+ DARM3_DARM3T_L1+ DARM3T_KNOK3T_L1+ BAST3_KNOK3T_L1+ KNOK3_KNOK3T_L1 Spring Week



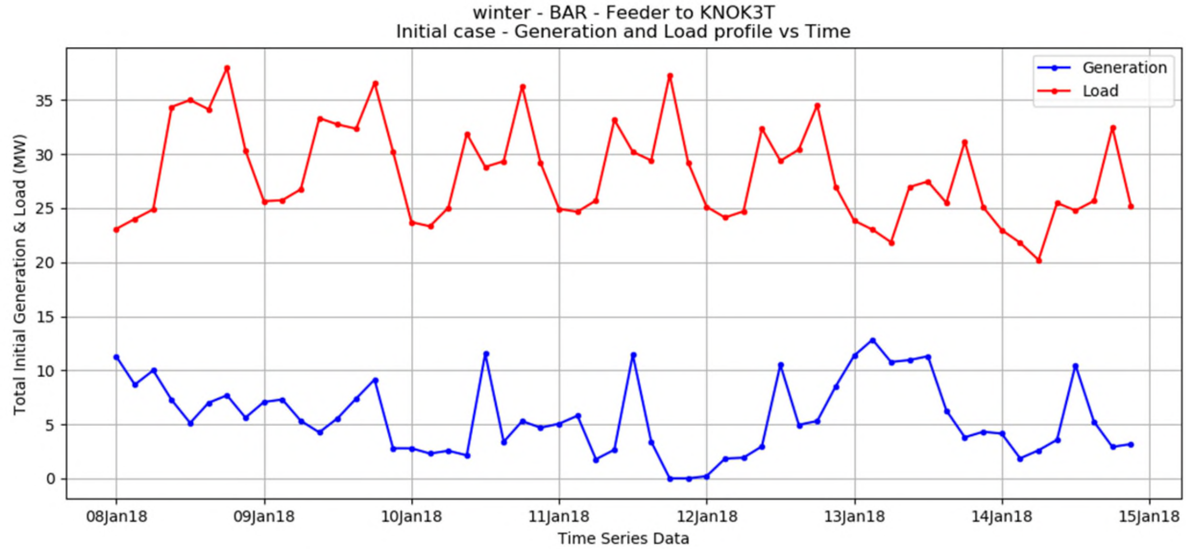
E.2.10. Best Contingency TORR3K_DARM3T_L1+ DARM3_DARM3T_L1+ DARM3T_KNOK3T_L1+ BAST3_KNOK3T_L1+ KNOK3_KNOK3T_L1 Summer Week

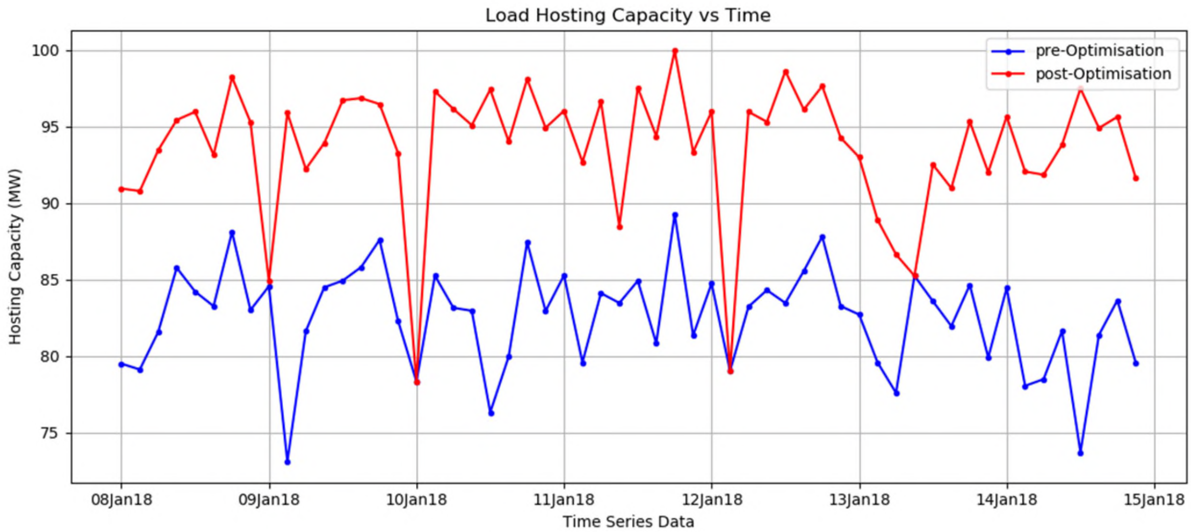


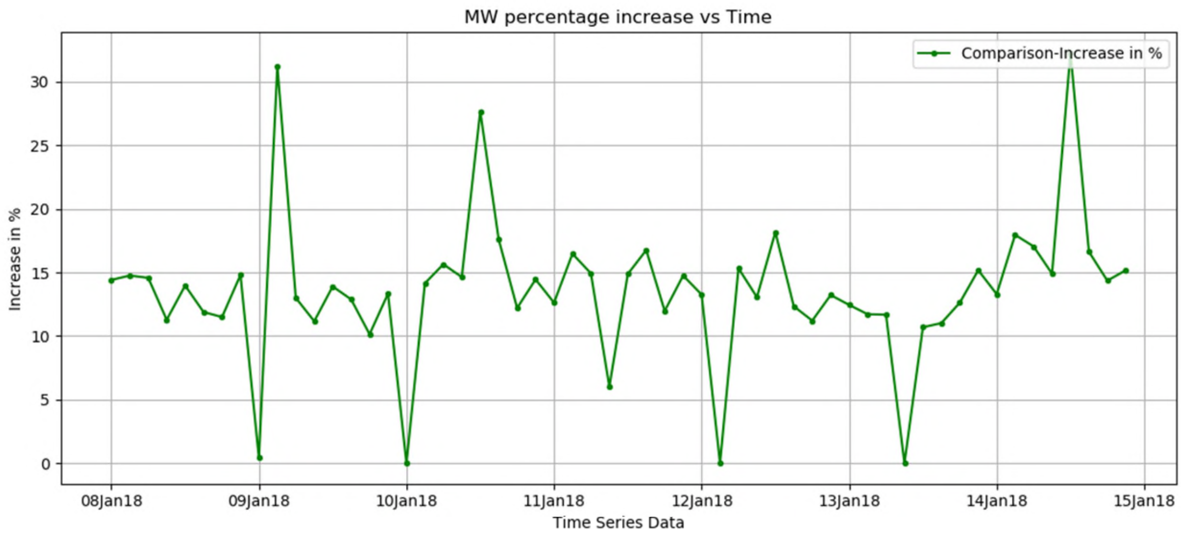
E.2.11. Best Contingency TORR3K_DARM3T_L1+ DARM3_DARM3T_L1+ DARM3T_KNOK3T_L1+ BAST3_KNOK3T_L1+ KNOK3_KNOK3T_L1 Autumn Week



E.2.12. Best Contingency TORR3K_DARM3T_L1+ DARM3_DARM3T_L1+ DARM3T_KNOK3T_L1+ BAST3_KNOK3T_L1+ KNOK3_KNOK3T_L1 Winter Week

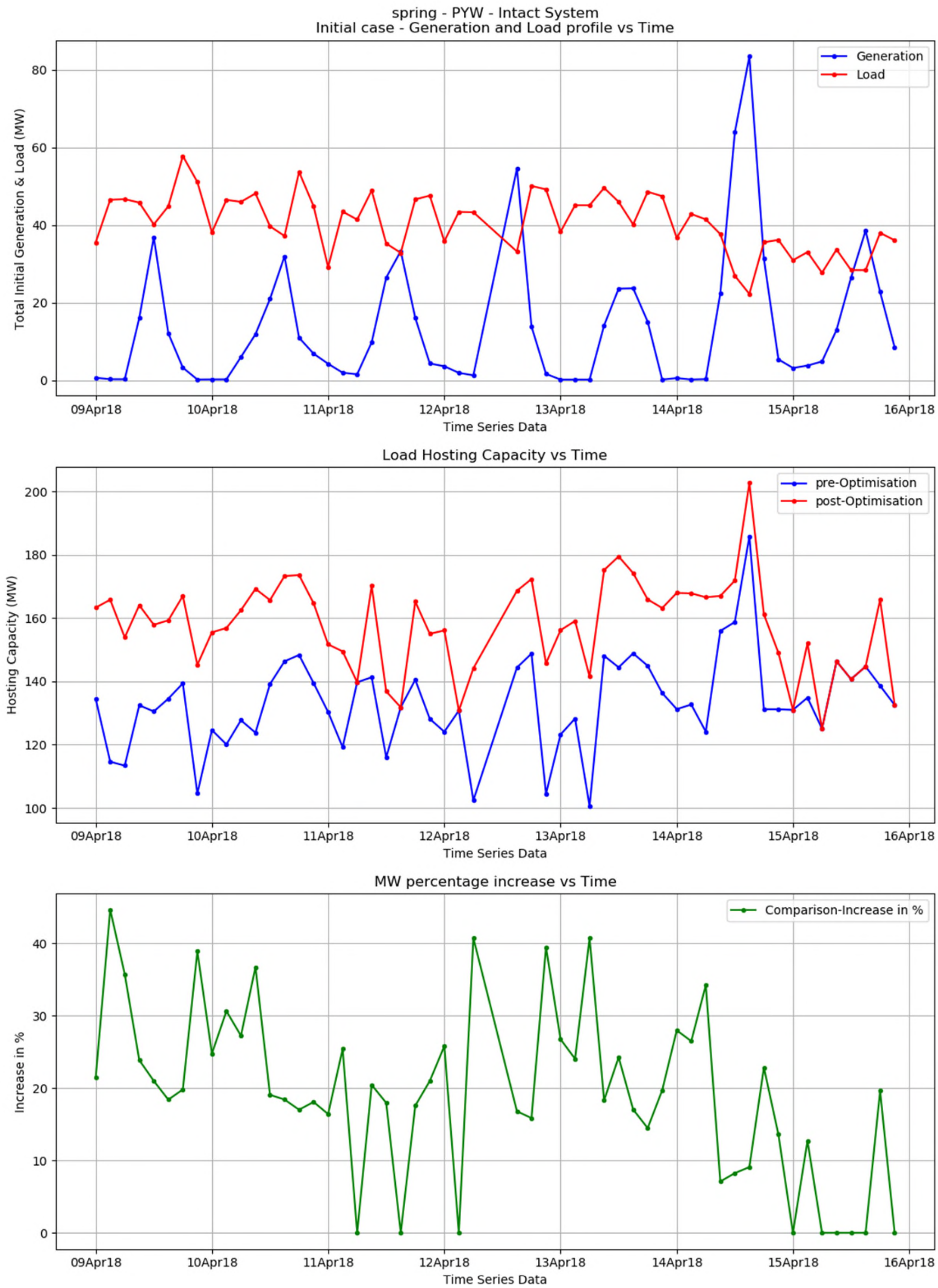




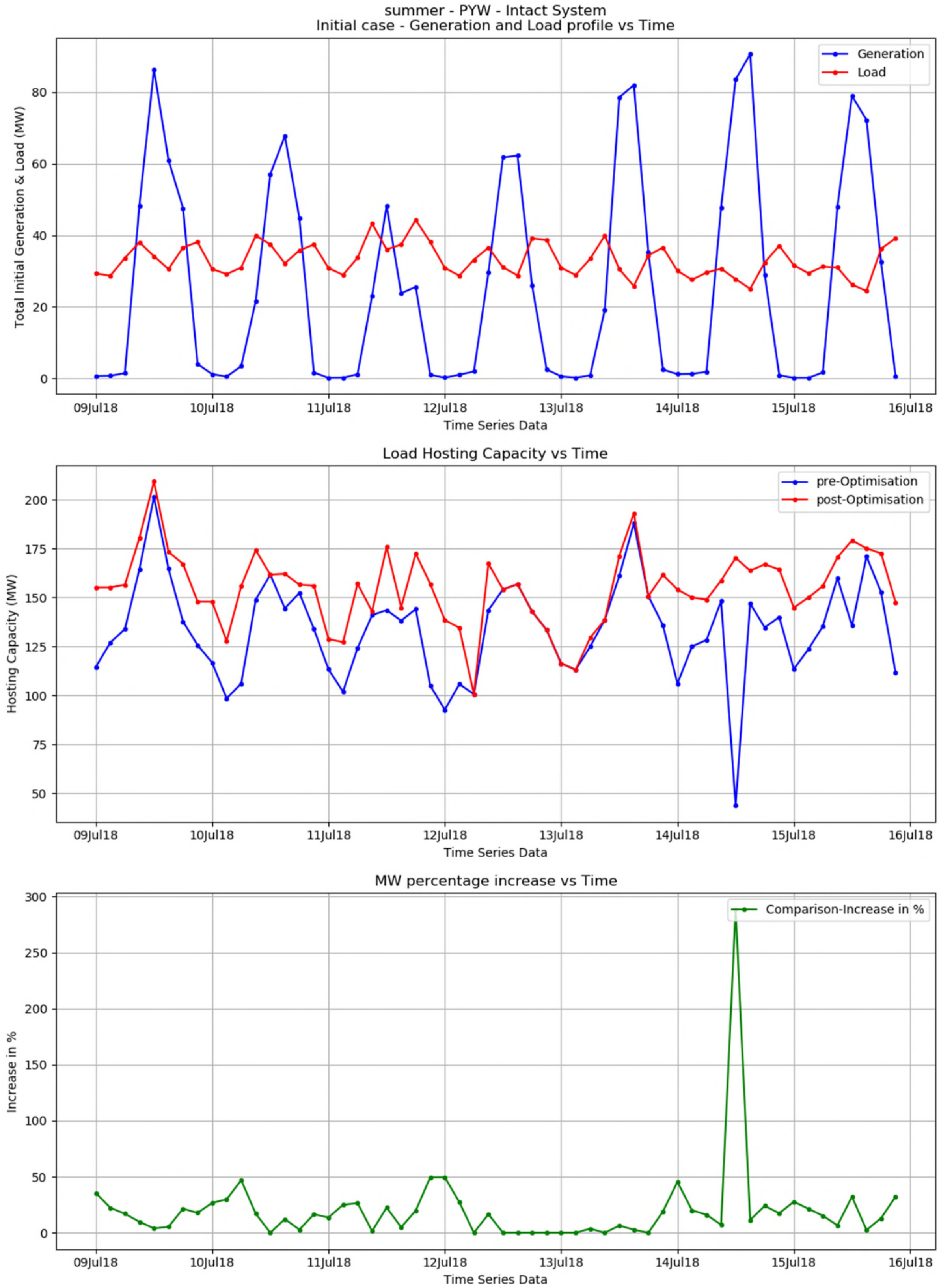


E.3. Pyworthy and North Tawton 33 kV BSPs

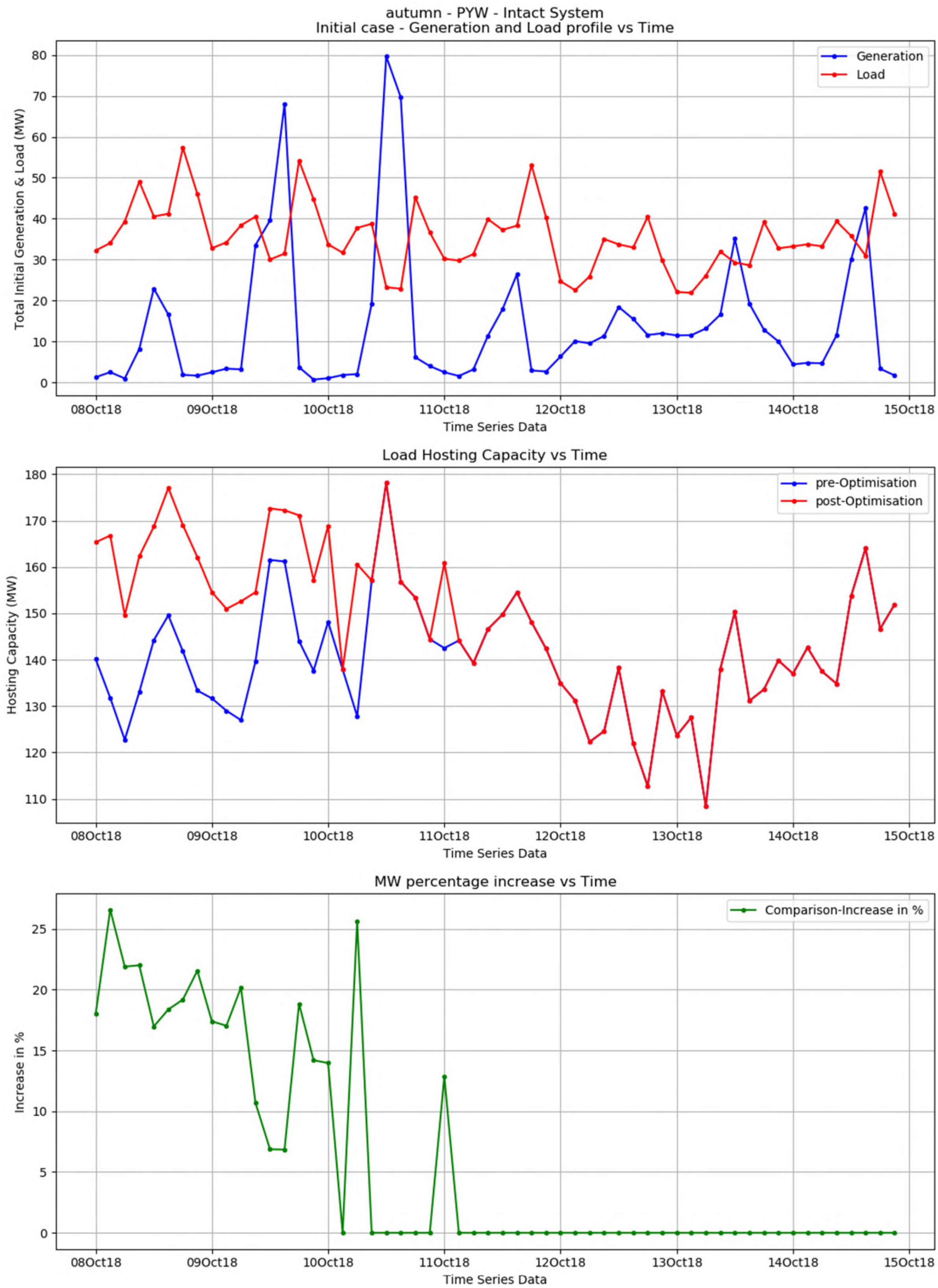
E.3.1. Intact System Spring Week



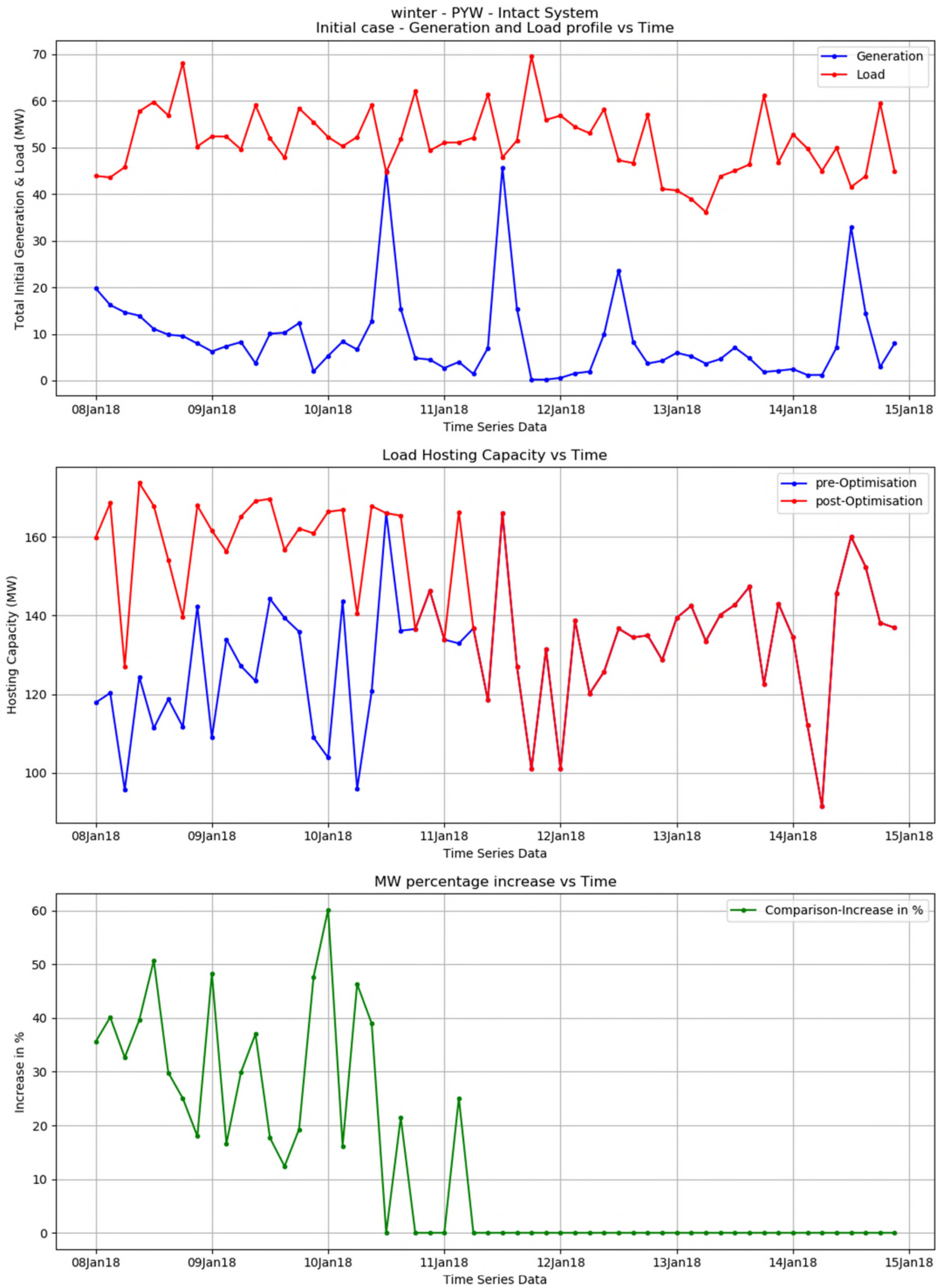
E.3.2. Intact System Summer Week



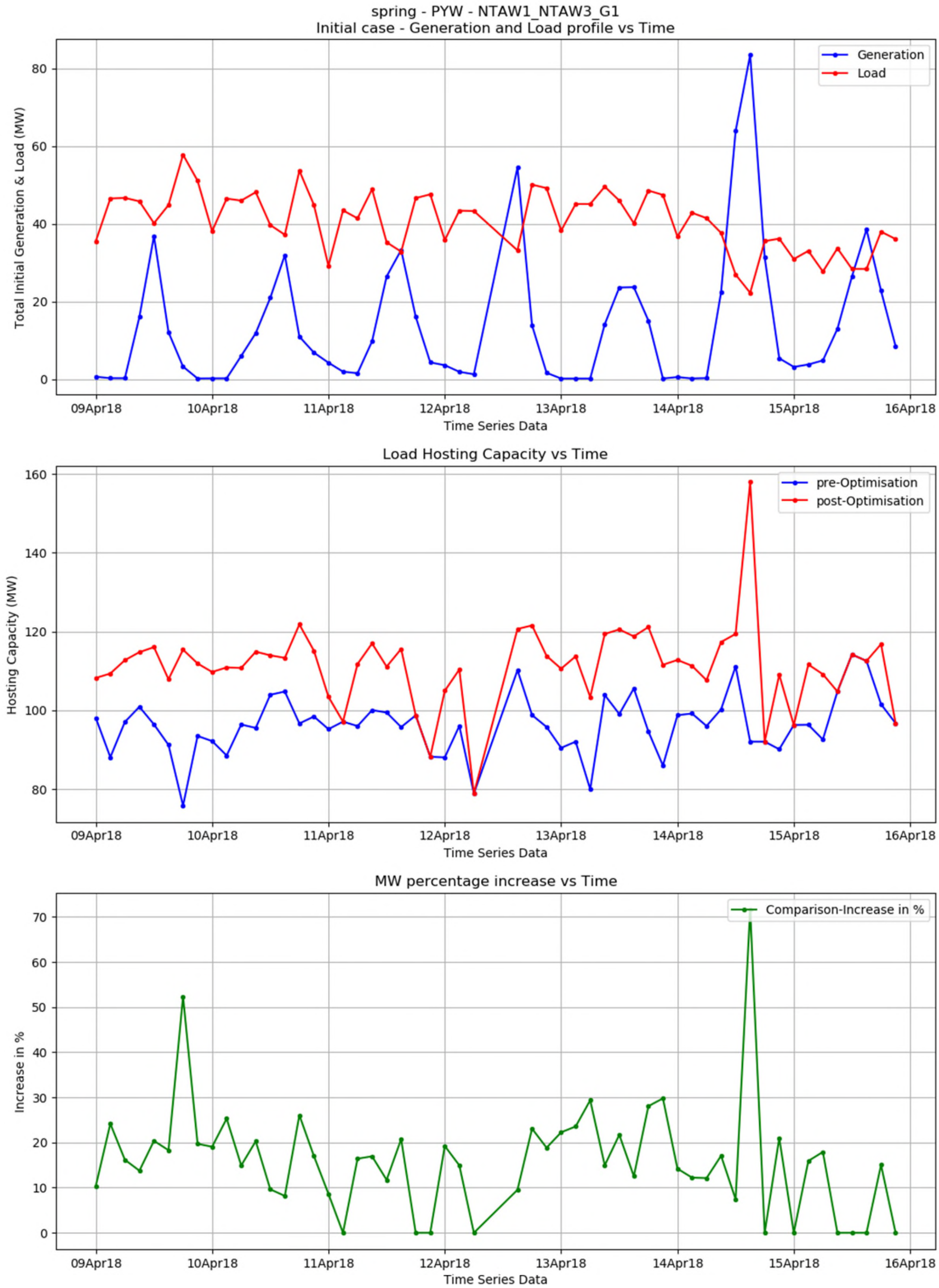
E.3.3. Intact System Autumn Week



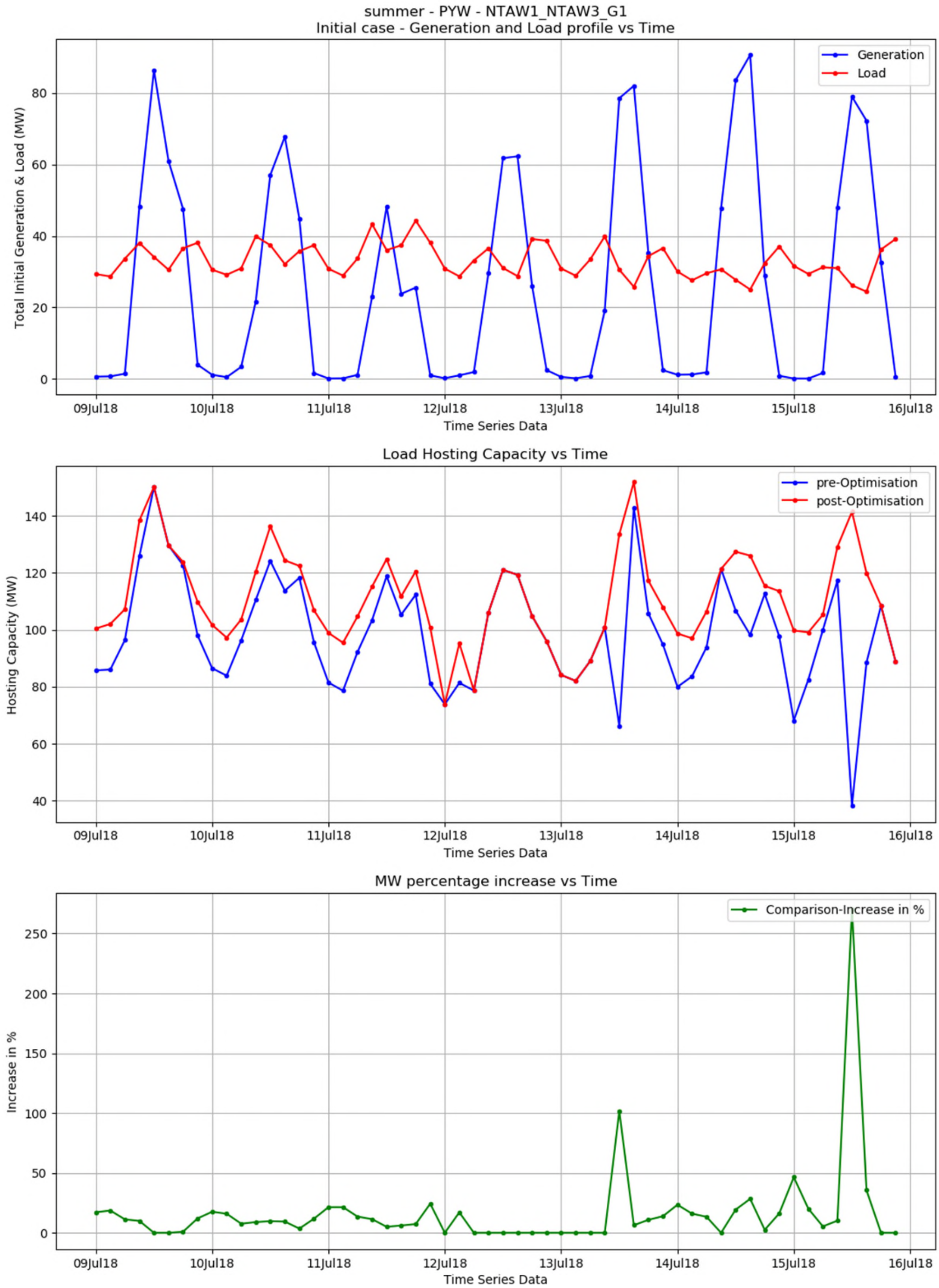
E.3.4. Intact System Winter Week



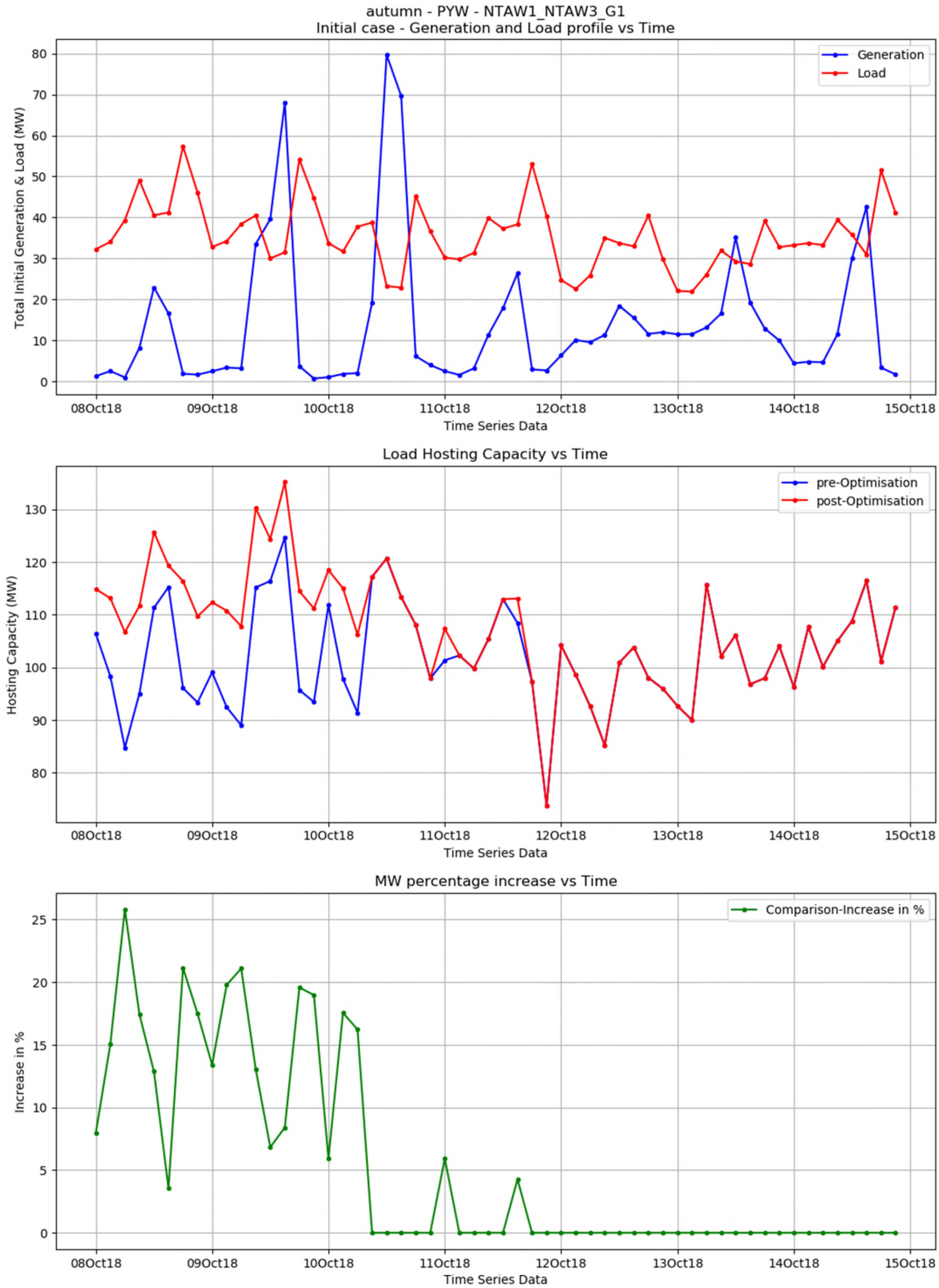
E.3.5. Worst Contingency NTAW1_NTAW3_G1 Spring Week



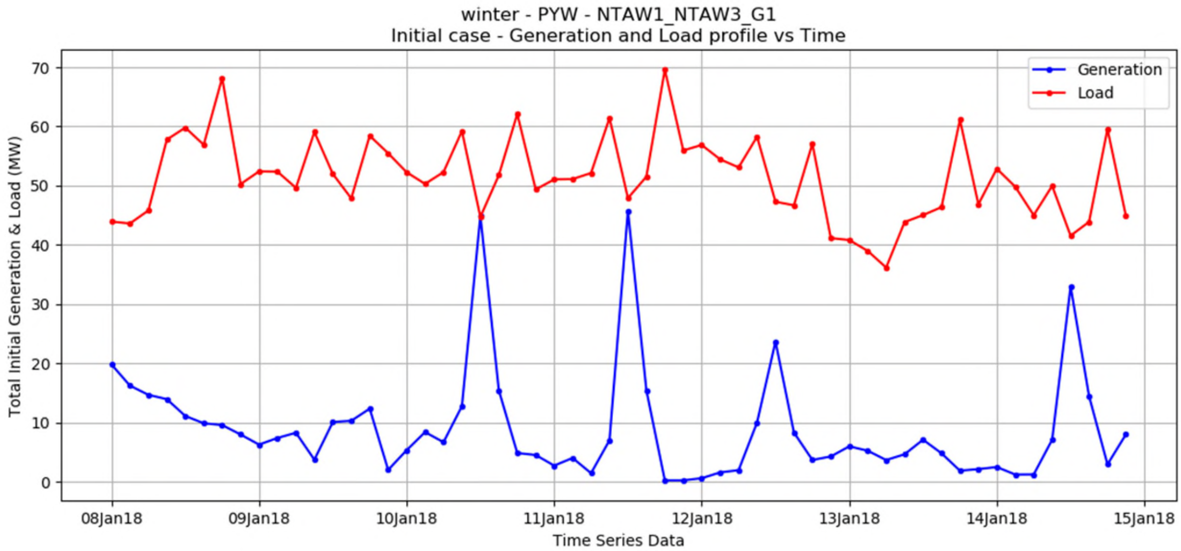
E.3.6. Worst Contingency NTAW1_NTAW3_G1 Summer Week

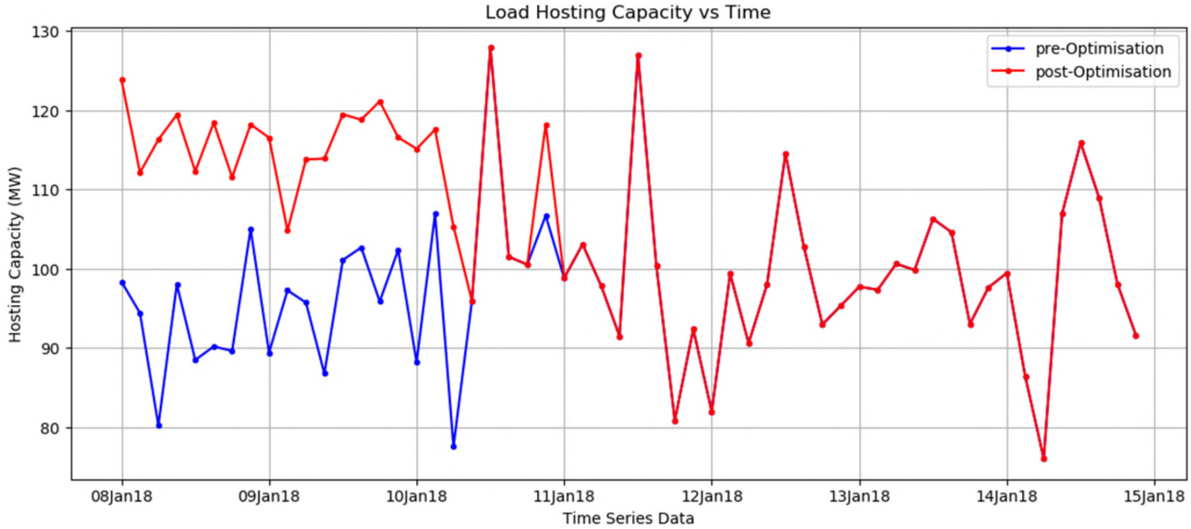


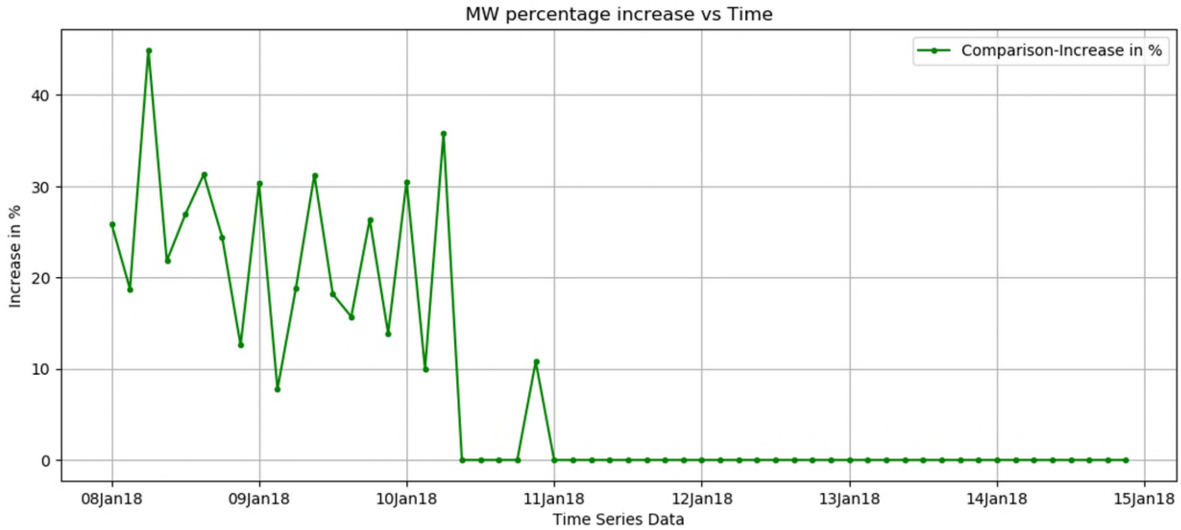
E.3.7. Worst Contingency NTAW1_NTAW3_G1 Autumn Week



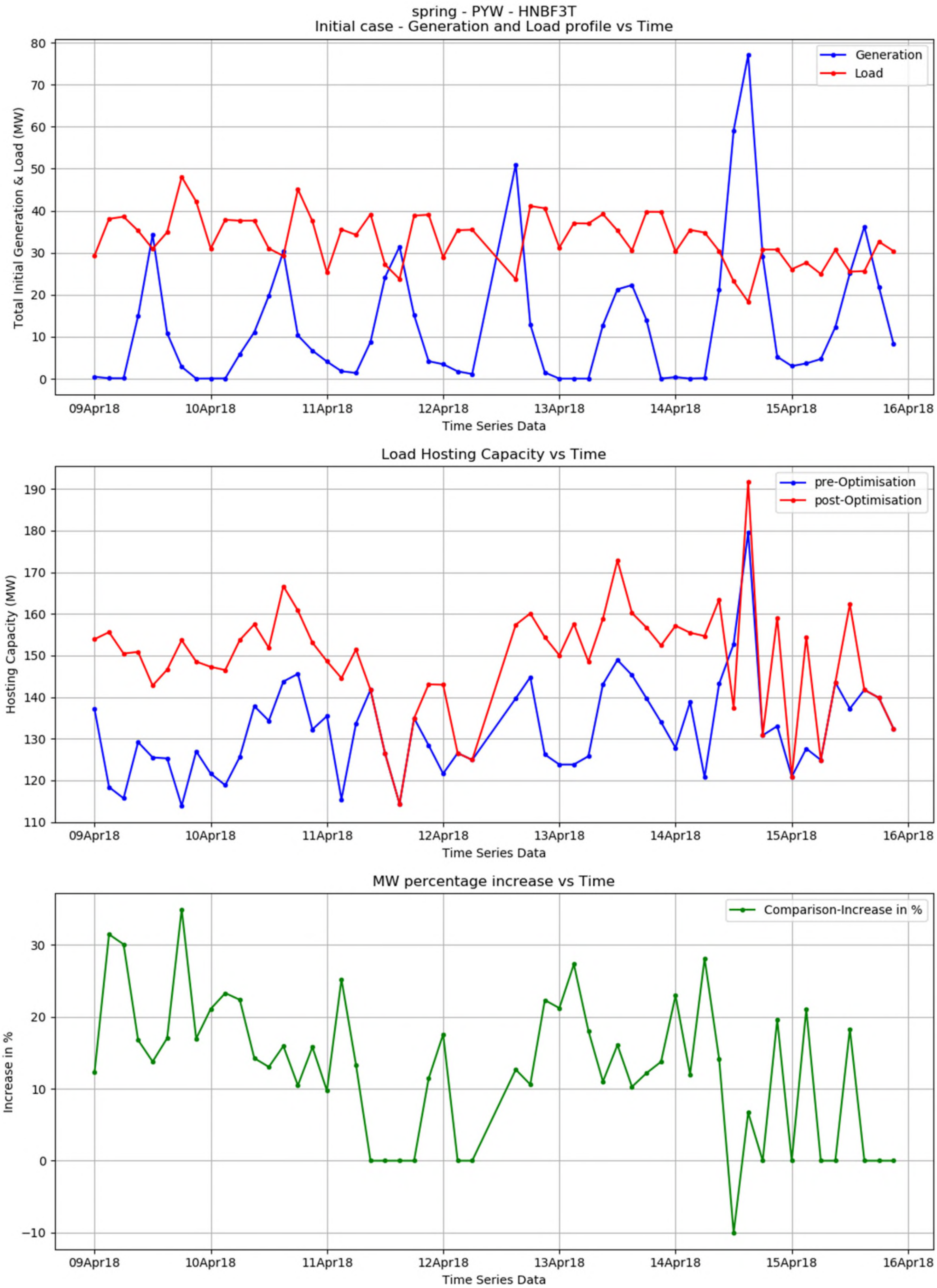
E.3.8. Worst Contingency NTAW1_NTAW3_G1 Winter Week



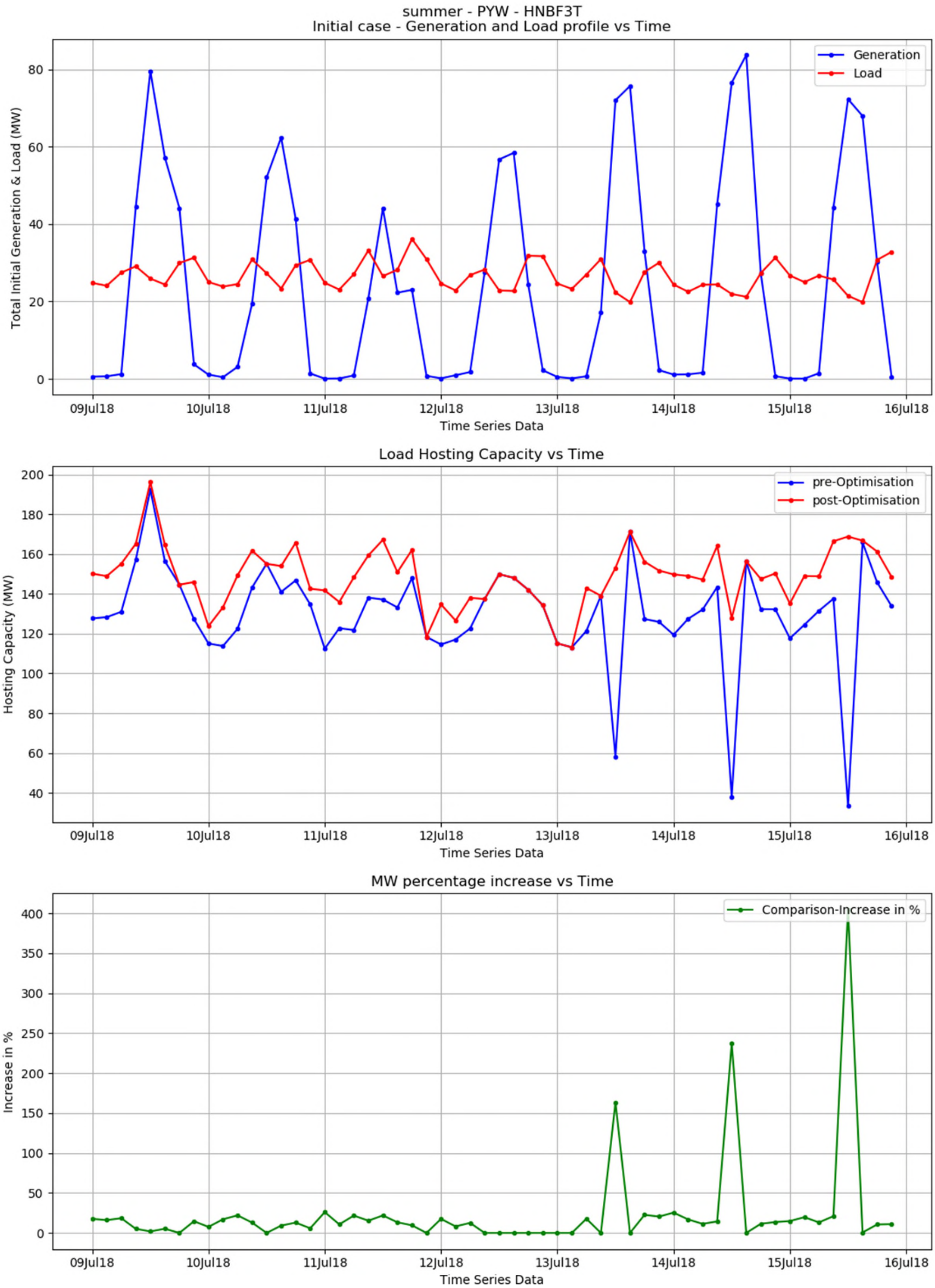




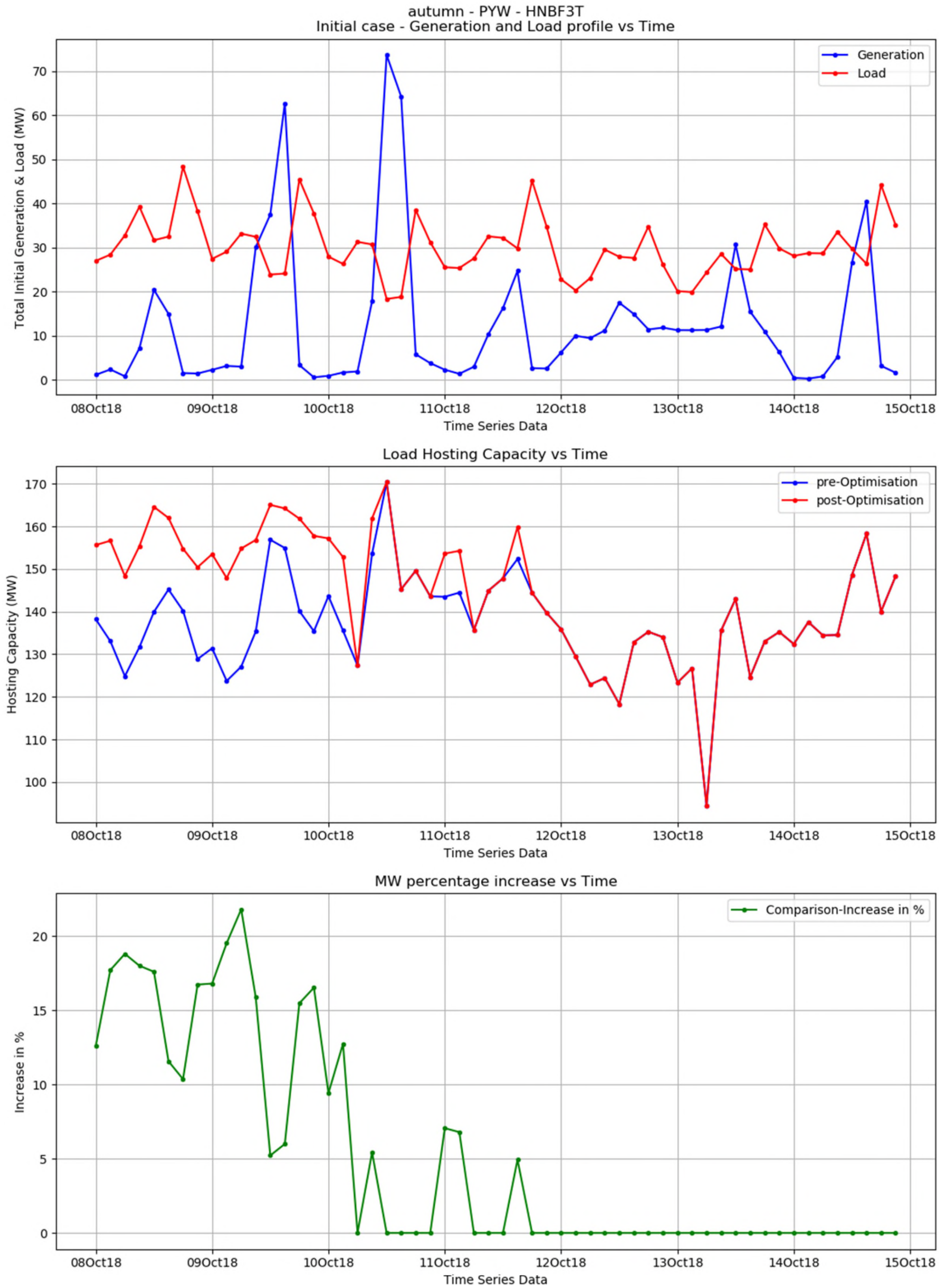
E.3.9. Best Contingency LAUN3K_HNBF3T_L2+ ECUR3_HNBF3T_L2+ HNBF3_HNBF3T_L1 Spring Week



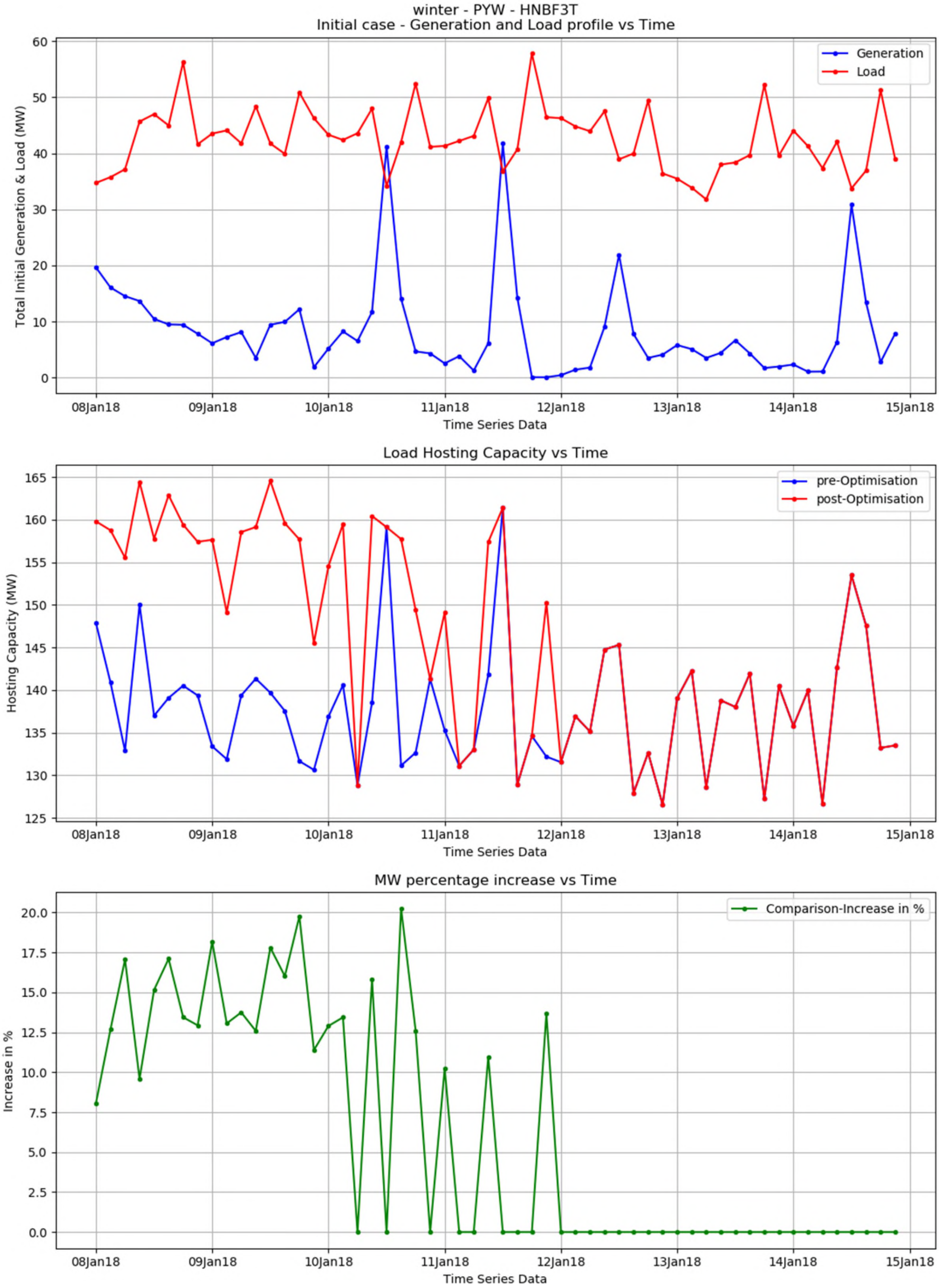
E.3.10. Best Contingency LAUN3K_HNBF3T_L2+ ECUR3_HNBF3T_L2+ HNBF3_HNBF3T_L1 Summer Week



E.3.11. Best Contingency LAUN3K_HNBF3T_L2+ ECUR3_HNBF3T_L2+ HNBF3_HNBF3T_L1 Autumn Week

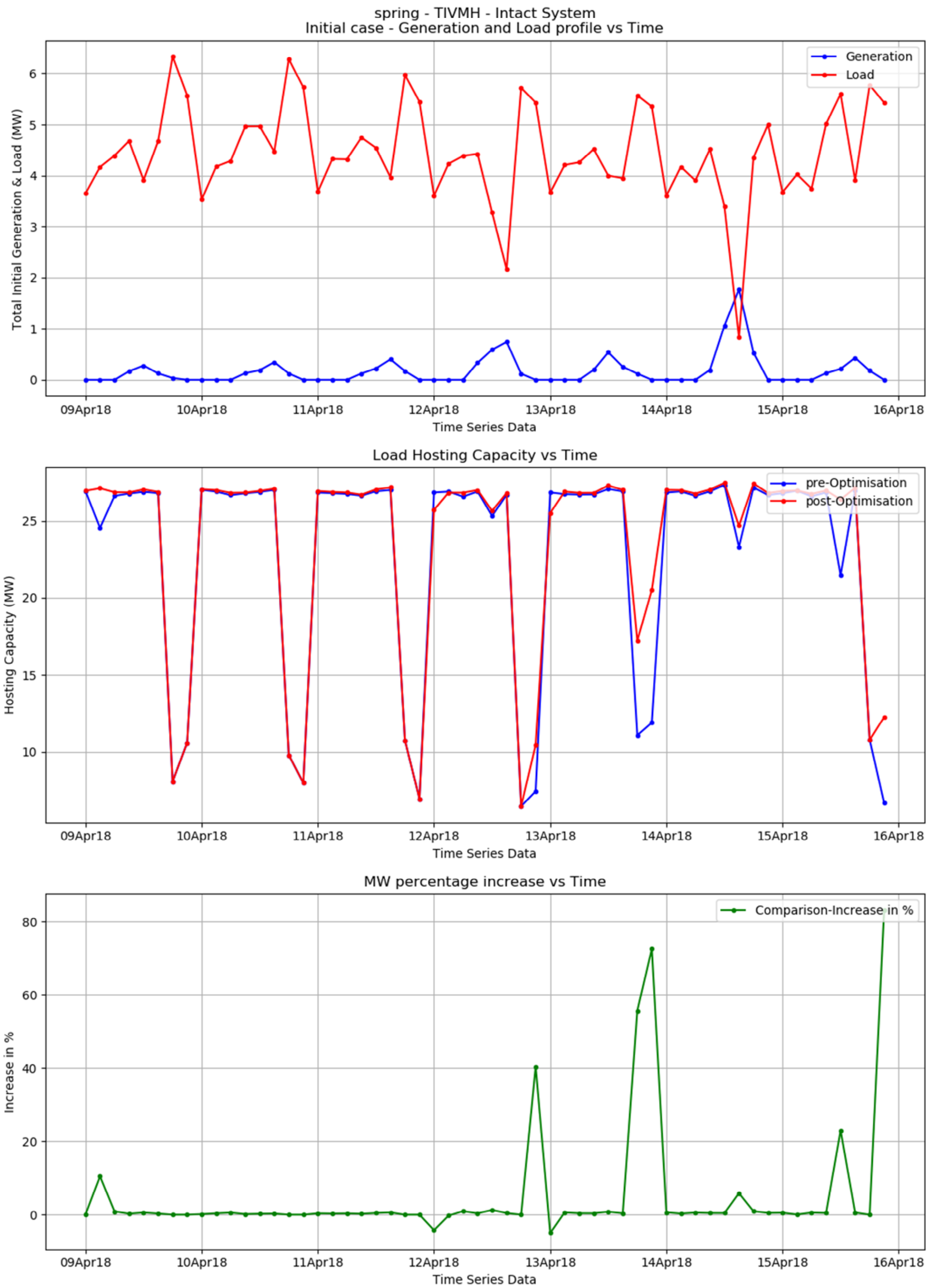


E.3.12. Best Contingency LAUN3K_HNBF3T_L2+ ECUR3_HNBF3T_L2+ HNBF3_HNBF3T_L1 Winter Week

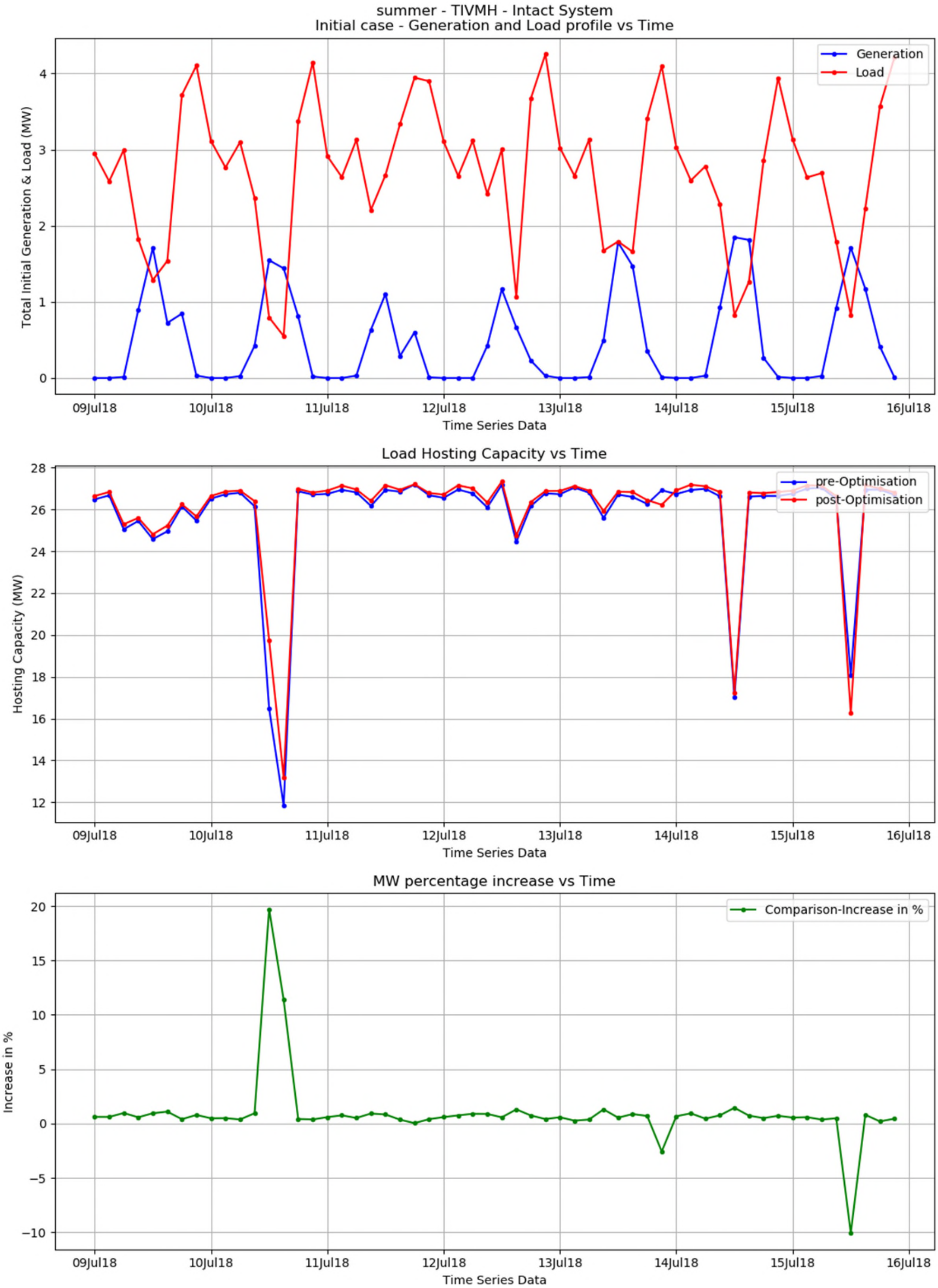


E.4. Tiverton Moorhayes 11kV Primary

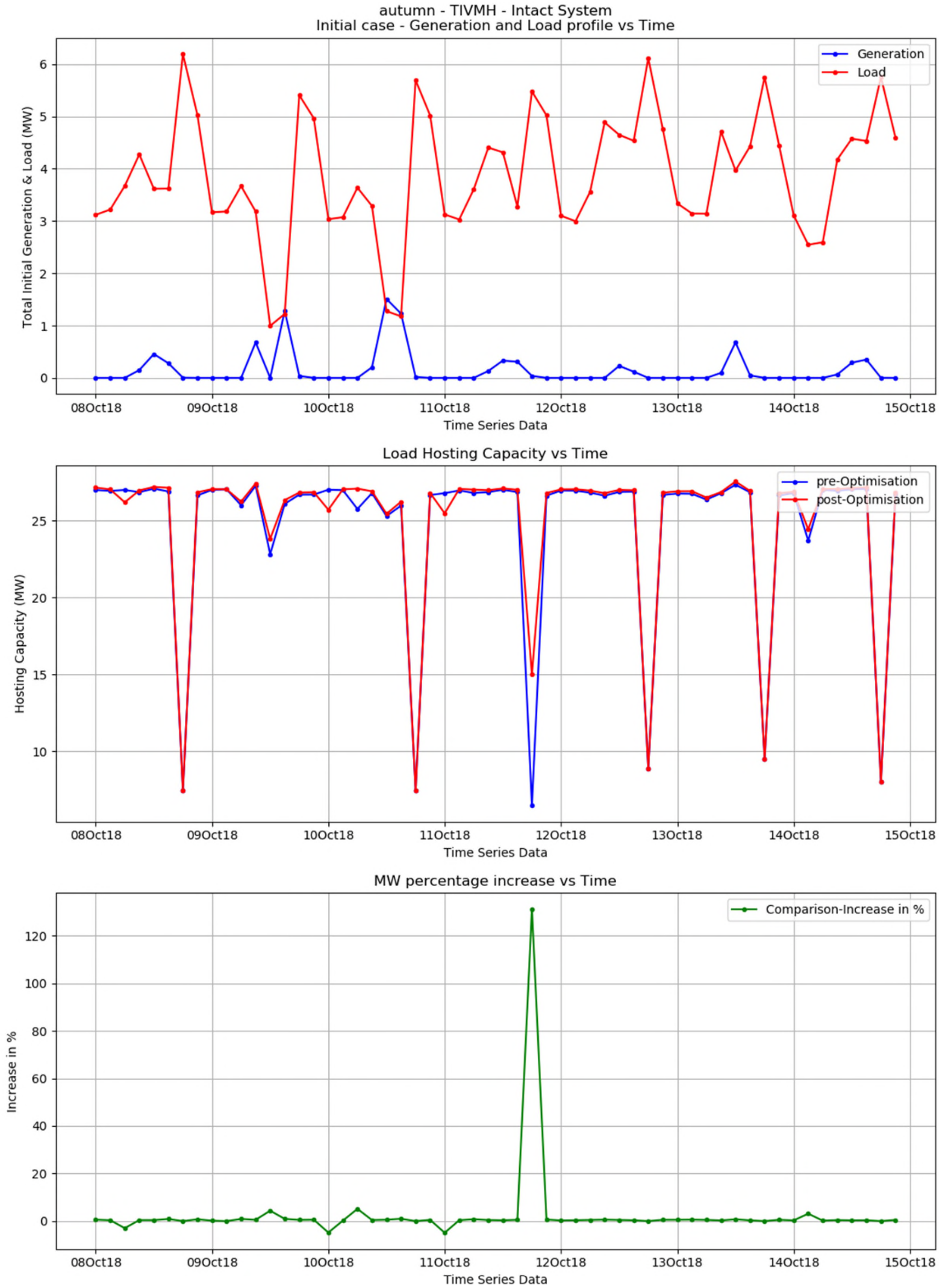
E.4.1. Intact System Spring Week



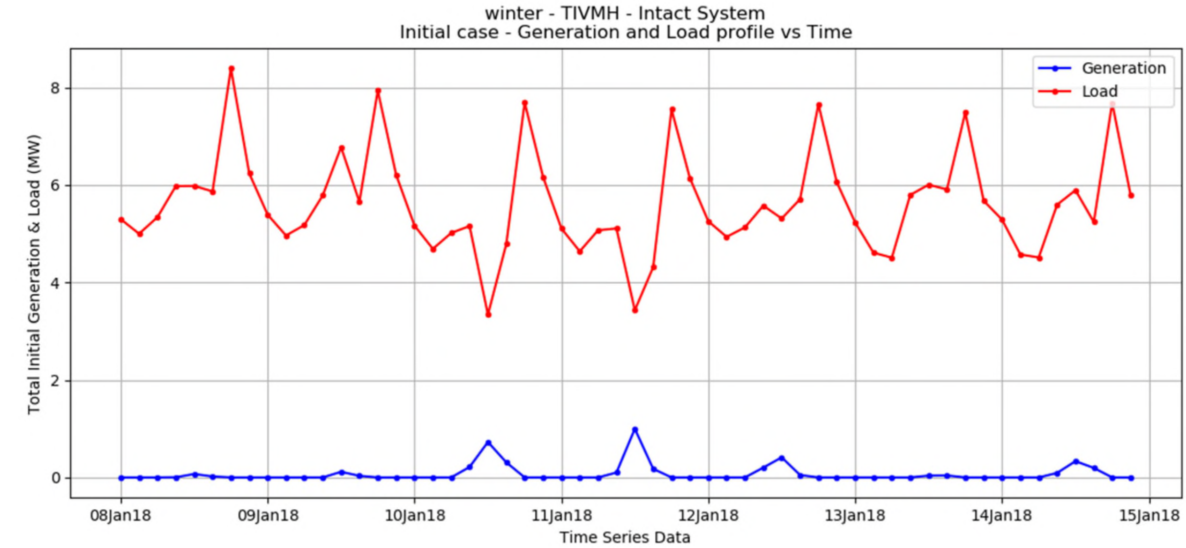
E.4.2. Intact System Summer Week

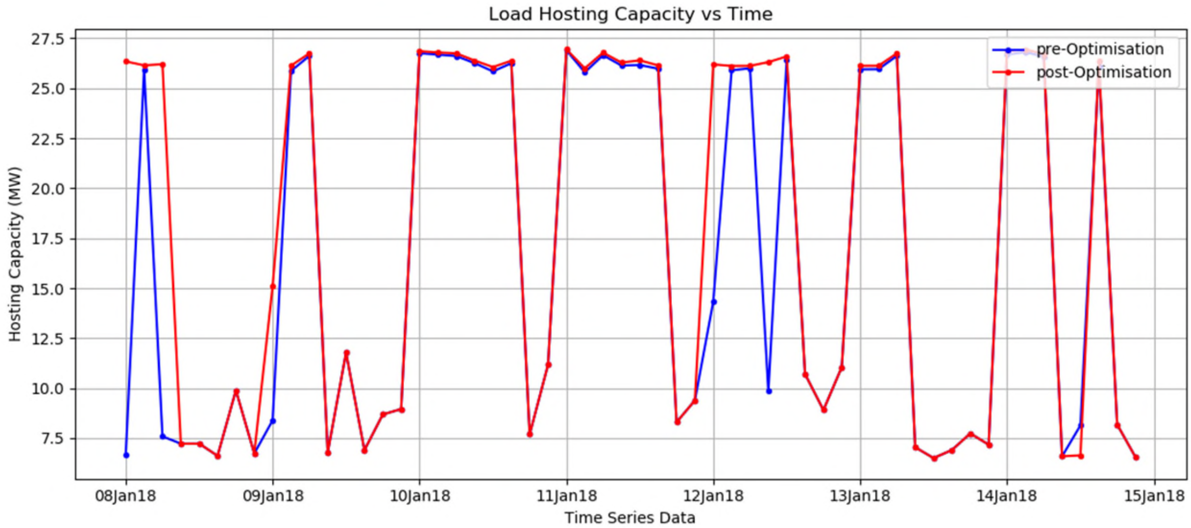


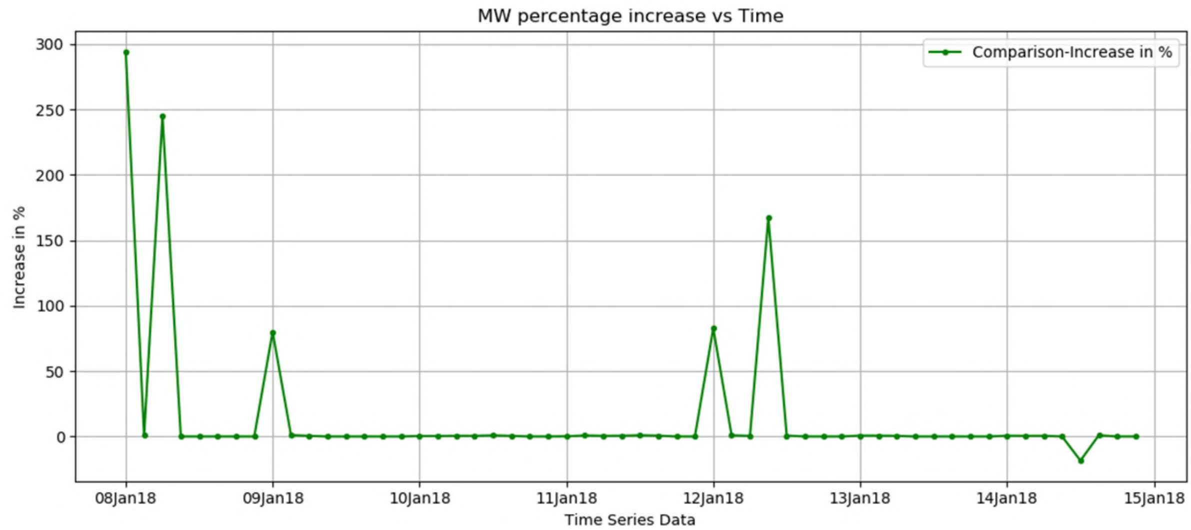
E.4.3. Intact System Autumn Week



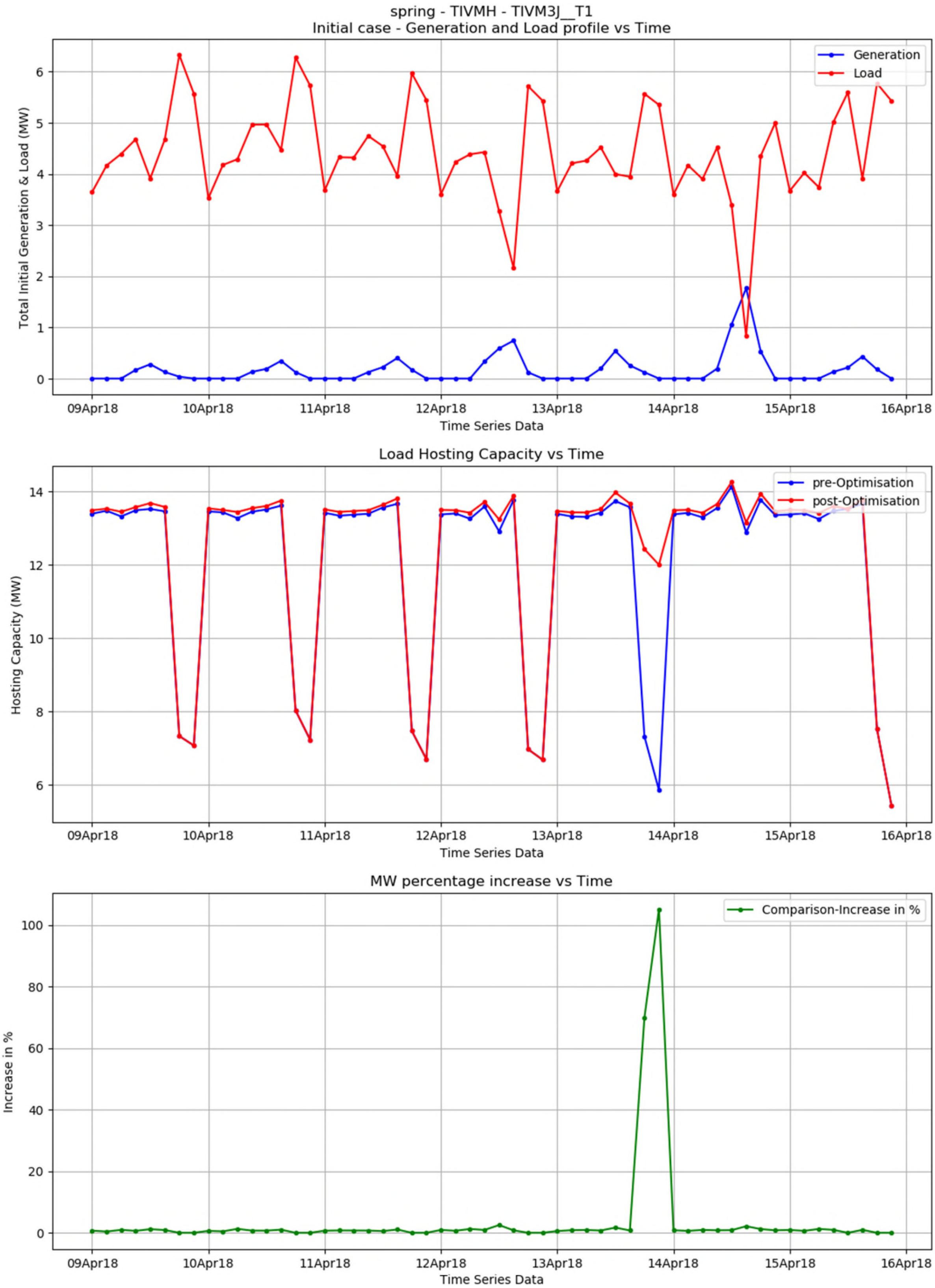
E.4.4. Intact System Winter Week



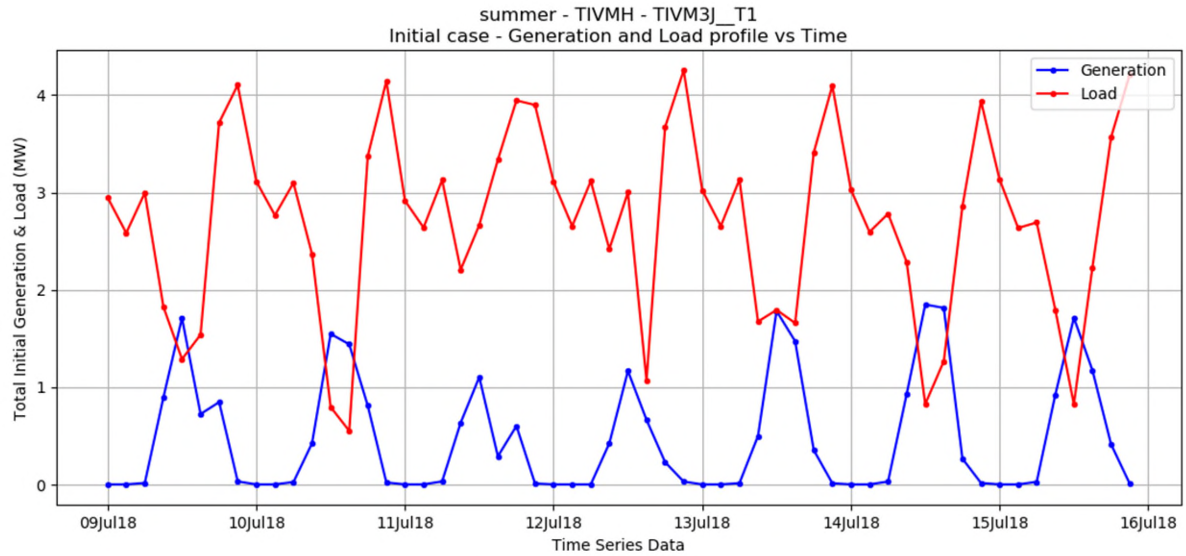


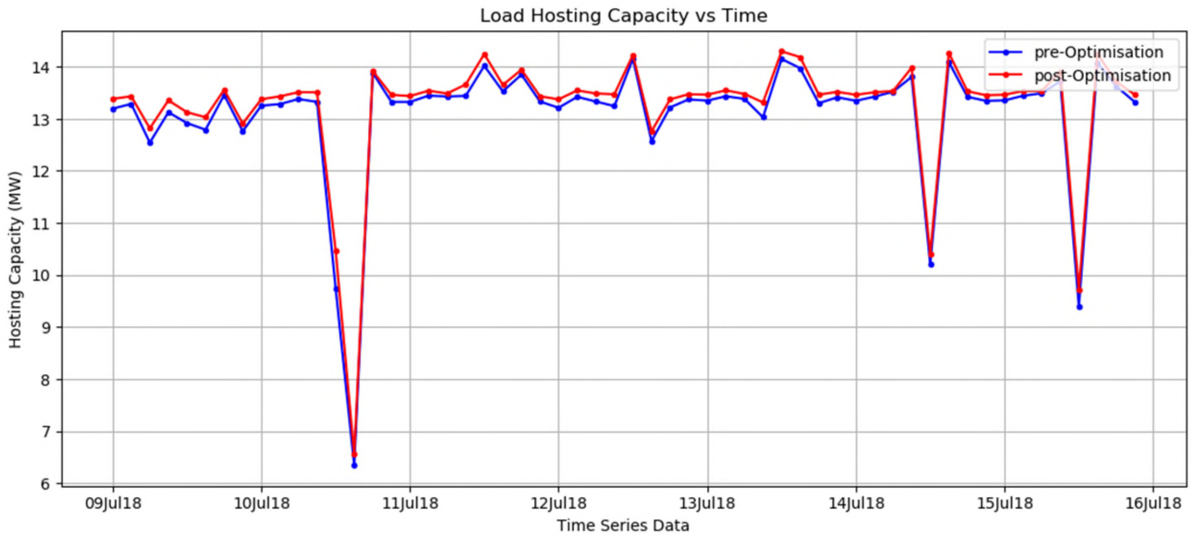


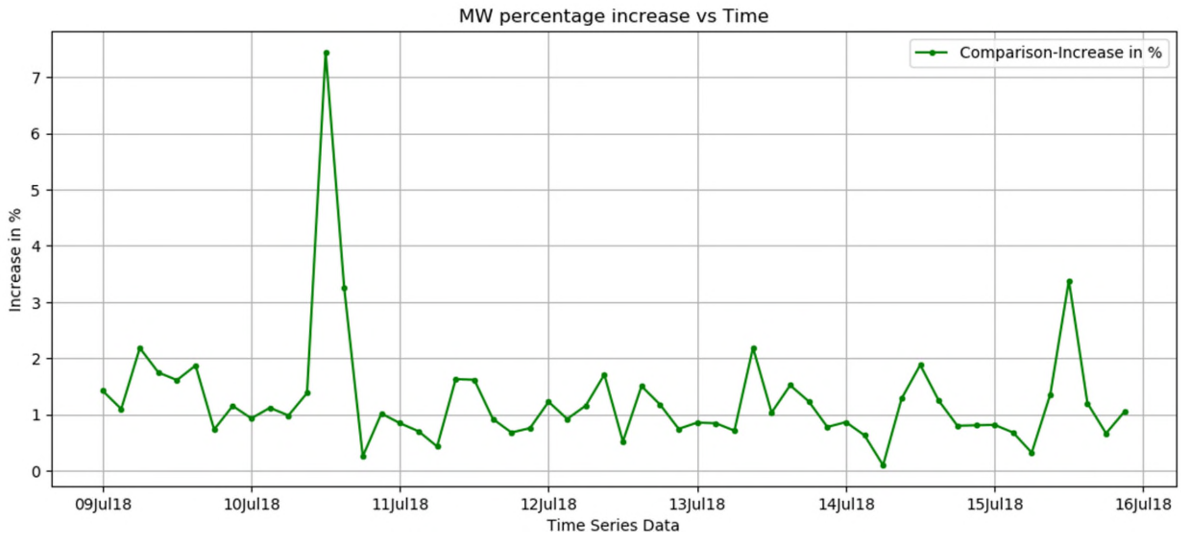
E.4.5. Worst Contingency TIVM3J__T1 Spring Week



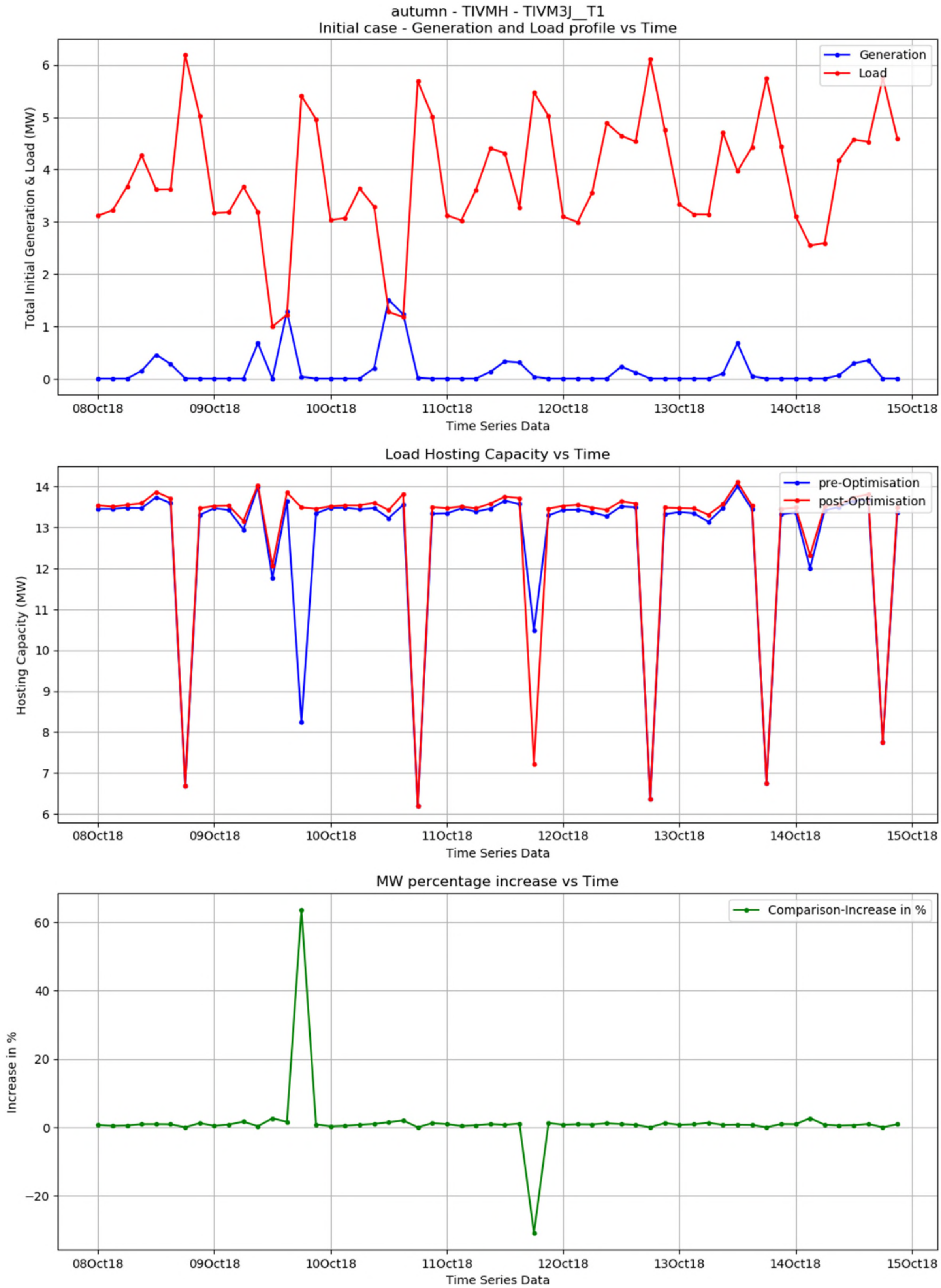
E.4.6. Worst Contingency TIVM3J__T1 Summer Week



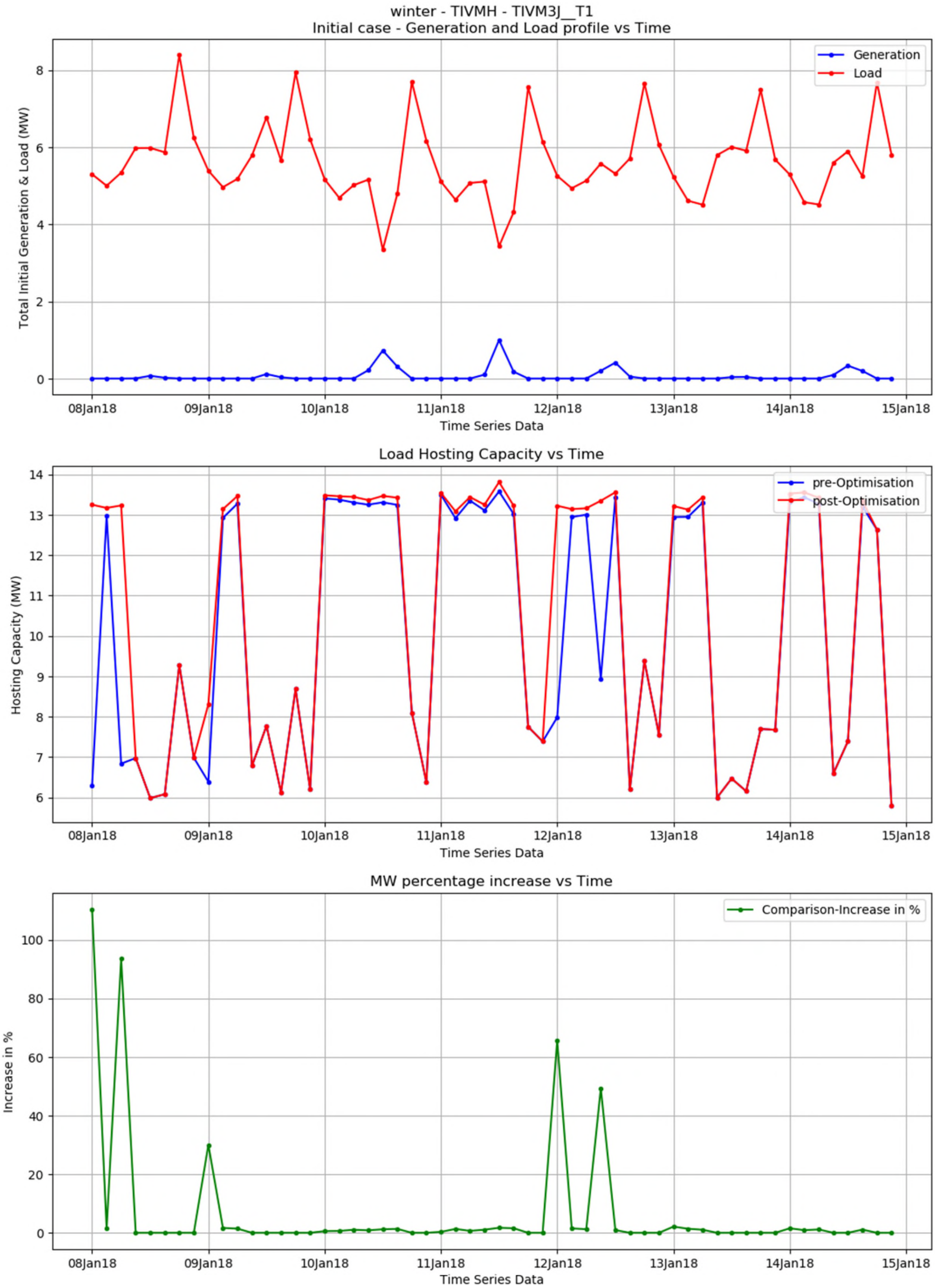




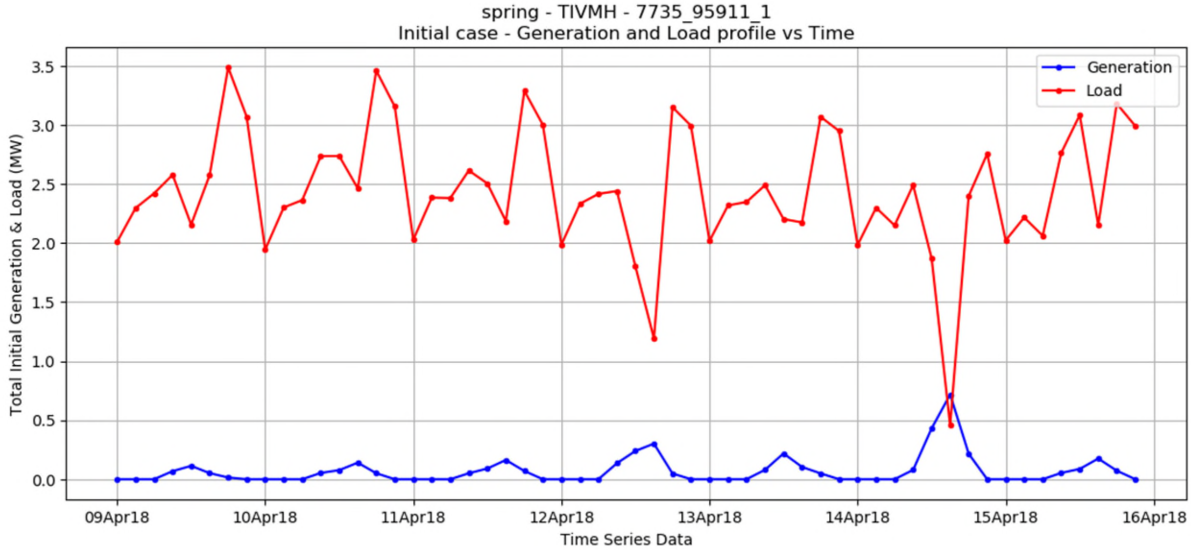
E.4.7. Worst Contingency TIVM3J__T1 Autumn Week

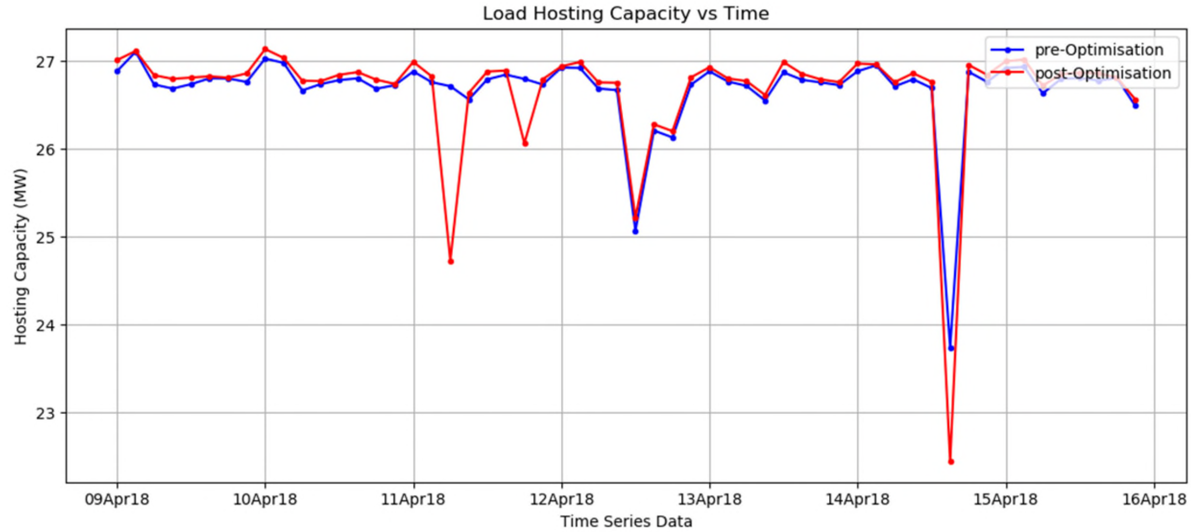


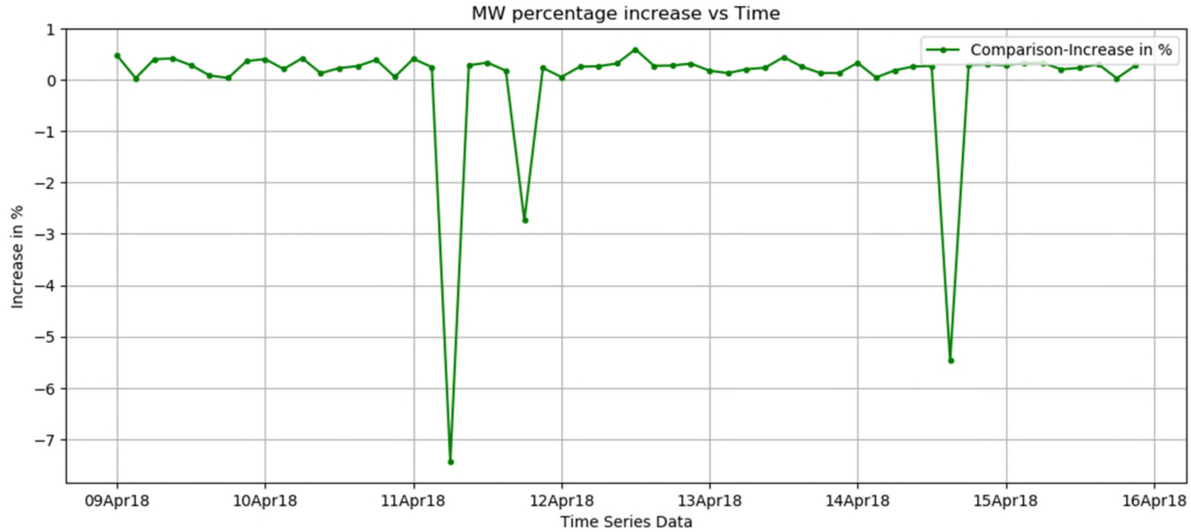
E.4.8. Worst Contingency TIVM3J__T1 Winter Week



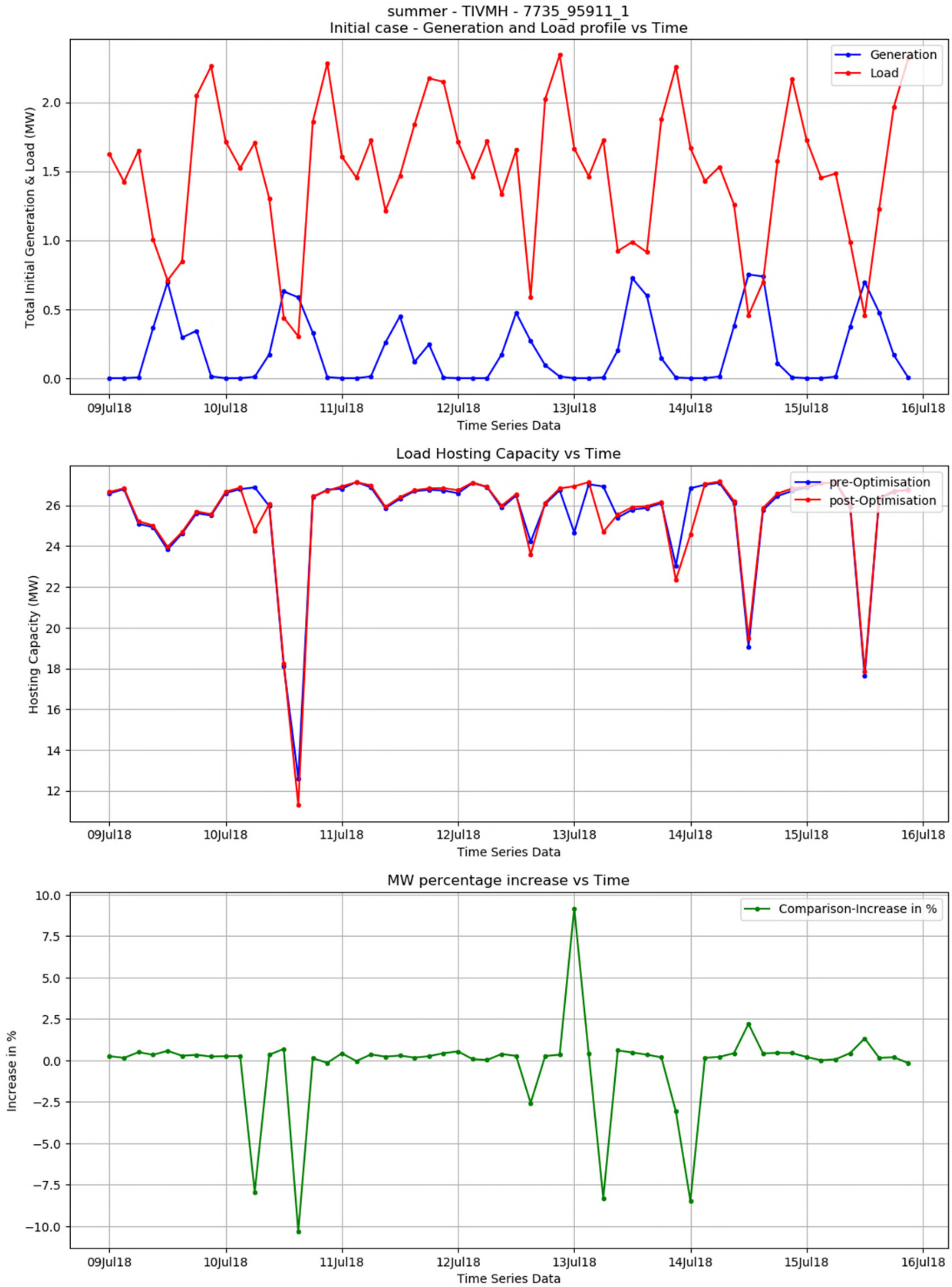
E.4.9. Best Contingency 7735_95911_1 Spring Week



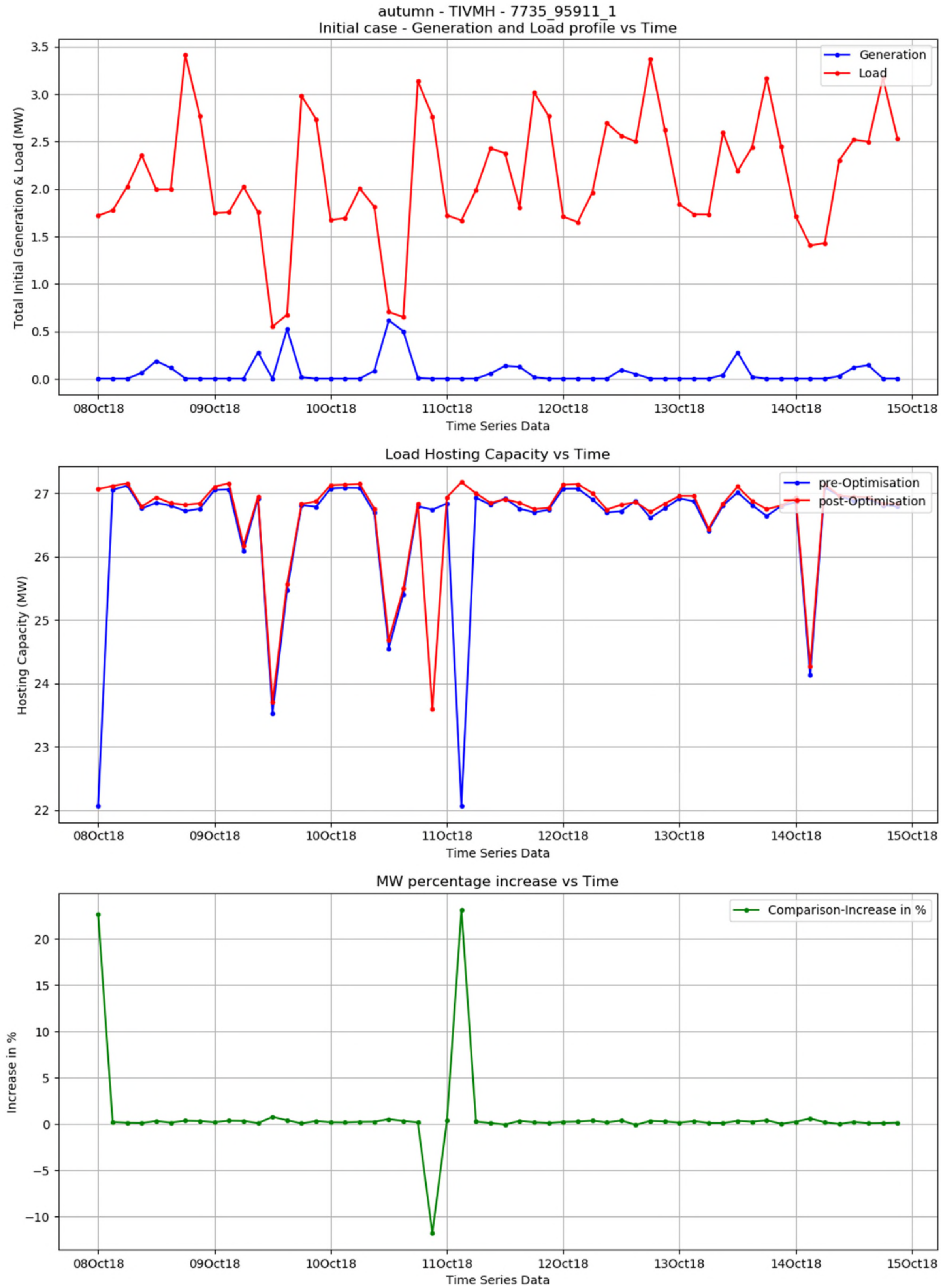




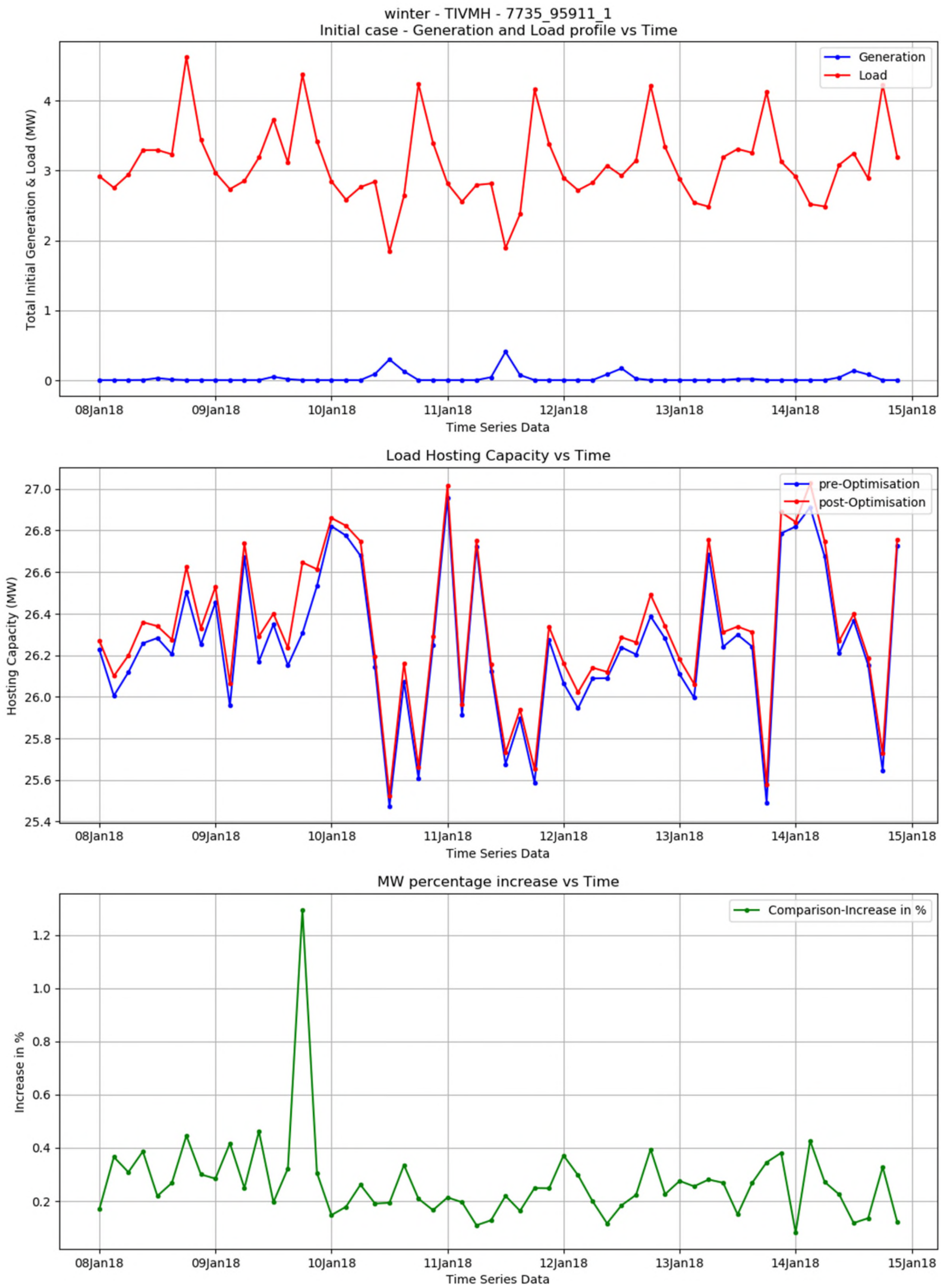
E.4.10. Best Contingency 7735_95911_1 Summer Week



E.4.11. Best Contingency 7735_95911_1 Autumn Week



E.4.12. Best Contingency 7735_95911_1 Winter Week



Appendix F Technical Assumptions Log

No.	Assumption	Details of Assumption
TA-001	Branches in BSP and Primary networks are made up of AC lines and 2 winding devices only, this includes the 132/33 kV zone tie transformers.	This assumption is based on the PSSE models provided and the LTDS SLD which have no BSP/Primary networks with 3 winding transformers.
TA-002	BSP main voltage is 33 kV and Primary's voltage is 11 kV.	
TA-003	In 11 kV Primary cases - only branches connected to the Primary bus bar will be treated as contingencies.	
TA-004	T'ed connections are identified by letter T at the end of the bus name in PSSE. (only line branches are considered for T'ed connections)	This assumption is uses when determining T-circuit contingencies.
TA-005	L0 are not considered as a contingency unless it is a feeder in 11 kV Primary	
TA-006	33/11 kV Transformer RPF overloads in initial cases will be corrected prior to any studies, it assumed to these will be resolved by traditional methods.	
TA-007	Primary's are modelled with slack bus generation on the 33 kV bus of the Primary 33/11 kV Transformers.	
TA-008	Mvar availability of generation is based on MVA rating and +/-0.95 power factor.	To account for the situation where the generator has low MW dispatch but high Mvar availability.
TA-009	Busses below 11 kV are ignored by the algorithms	This is to ignore earthing transformer that are sometimes present in WPD PSSE models
TA-010	Tie transformers (i.e. 132/33 kV in BSP networks and 33/11 kV in Primary networks) have there taps lock when scaling generation or load	

Pure Offices, Lakeview House, Wilton Drive, Warwick CV34 6RG, United Kingdom

P: +44 1926 675 851 W: https://www.pscconsulting.com