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Technical Report TA User Project

DSM and VC based Reliability and Stability Analysis of Microgrid with Renewable Energy-(DSM-RSAMRE)

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Abbreviations

CVC	*Coordinated Voltage Control*
CHIL	Control Hardware In the Loop
DER	Distributed Energy Resource
DFIG	Double Fed Induction Generator
DG	Distributed Generation
DNO	*Distributed Network Operator*
FLC	*Fuzzy Logic Control*
ICT	*Information and Communication Technologies*
MG	Microgrid
OLTC	*On Load Tap Changer*
PC	*Power Curtailment (PC)*
PFC	*Power Factor Control*
PMU	*Phasor measurement Unit*
PV	*Photovoltaic*
RES	Renewable Energy Sources
RSCAD	Real Time Digital Simulation Software
SIL	Software In the Loop
SGCA	Smart Grid Control Algorithm
TA	Trans-national Access

Executive Summary

It has been noted recently that the world's electricity systems are starting to “decentralize, decarbonize, and democratize”. These trends make microgrids and distributed generation systems more important. Therefore, development of advanced tools/platforms for testing operation and control of microgrid has attracted more and more attention nowadays.

The one of the most important problems of microgrid is voltage excursions. This project deals with developing a coordinated voltage control method that will ensure the voltage stability of a microgrid that contain wind and solar power systems. In this project, the microgrid was controlled by fuzzy logic-controller. Designed fuzzy logic-based voltage control system decided which control method was appropriate for the system before controlling it. Also, this controller increased the voltage stability of the network system.

In this project, a microgrid was created with seven bus system model that consists of a wind power system, a PV power system, an OLTC (On Load Tap Changer) controlled main power transformer and different loads in real time digital simulator software (RSCAD). All of the buses voltage was measured by phasor measurement units (PMU) and this data was transferred to MATLAB/Simulink software. Designed fuzzy Logic based voltage-controlled system was also modelled in MATLAB/Simulink software. Matlab/Simulink and RSCAD software have online communication system with each other by TCP-IP protocols. Initially the voltage was checked at each load buses of the network. If the voltage limits are violated at any nodes, fuzzy logic controller decides which control method use. The control algorithm had three control outputs that are the power factor control, the on load tap changer and the generation curtailment control.

Control signals were transmitted to OLTC system of main transformer, PV and Wind distributed generation systems by fuzzy logic controller. Thus, voltage of microgrid was controlled and stabilised by fuzzy logic-based controller.

The simulation results obtained twelve different cases consist of various buses voltage and DG’s output power conditions. For each condition buses voltage was recorded with and without controller. In each case recorded quantities were plotted and compared with unity power factor case. The results of this comparison indicated that the coordinated voltage control (CVC) algorithm can significantly keep the buses voltage in an acceptable range for operation.

1 General Information of the User Project

Distribution networks in different parts of the world have gone through significant growth and improvement with the utilization of distributed generation (DGs). This is line with the policies of government of countries towards the use of renewable energy resources technology. Previously, the distribution system has been working on a unidirectional power flow but with the connection of DGs, the system has to accept bidirectional power flows which resulted in several technical issues such as voltage levels and power flow, protection issues, equipment thermal ratings and fault current levels. One of the major concerns in the integration of DGs in the distribution systems is the voltage rise issue. This further requires the Distributed Network Operators (DNOs) to find solutions to the overvoltage problems in ensuring that the customers receive the voltage within its specified limits. Two main voltage control methods in a distribution system with DGs which have been identified are categorized as coordinated or centralized control while the other one is categorized as semi-coordinated and decentralized control. The coordinated control determines their control actions based on the information from the whole network, hence it requires data transfer and communications between the network nodes. Therefore, the aim of this project is to investigate the problems mentioned above. In this study, we developed coordinated voltage control algorithm which is capable of regulating the voltage either directly (OLTCs), or through the injection of active/reactive power, such as Photovoltaic (PV) inverters and curtailment of wind power. Management is based on the solution of an optimization problem, which minimizes a predefined objective function, that includes fuzzy constraints.

This proposal was submitted in the frame of the third ERIGrid TA call as a collaborative project among four universities, namely Dicle University (Turkey), Batman University (Turkey), University of Belgrade (Serbia) and University of Ljubljana(Slovenia). The proposed hosting laboratories were apart from AIT SmartEST(Smart Electricity Systems and Technologies Laboratory), TU Delft RTDS (Real Time Digital Simulation Laboratory) and ICCS – NTUA – EESL (Electric Energy Systems Laboratory). The host organization was selected to be TU Delft RTDS. Also, the initial visit plan involved a 4-week visit in July-August 2018. Eventually, the visit of the researchers took place between 16/07/2018 and 13/08/2018.

2 Research Motivation

The new trends of world's electricity systems aim to regulate electricity costs, improve flexibility and reliability, replace aging infrastructure, reduce CO_2 emissions to derogate climate change, and provide reliable electricity to areas lacking electrical infrastructure. Microgrids have emerged as a flexible architecture for deploying distributed energy resources (DERs) that can meet the wide-ranging needs of different communities from metropolitan cities to rural areas.

The operation of a microgrid becomes significantly complex with the high penetration of distributed energy resources (DERs), demand-side management (DSM), market operation, and disconnection and reconnection to the utility grid. Therefore, development of advanced tools/platforms for testing operation and control of microgrid has attracted more and more attention nowadays.

While using distributed generation (DG) systems, voltage regulation is likely to be affected because of the rapid changes in the levels of the generation and intermitting natural of source. One of the most important situations seen in microgrids are voltage excursions, which comes from voltage drops or voltage rises. The reason of this situation is disconnection or reconnection to the microgrid of DG's. To increase the reliability and stability of microgrid it is also crucial to reduce voltage excursion when a DG reconnected to microgrid. Voltage control methods are usually implemented as local solutions, with locally obtained measurements are used (e.g., power factor control or Q (V) Droop control of Inverters, voltage regulators, capacitor banks, etc.). As the distribution networks become more complex, more coordinated voltage control approaches, novel technologies, such as storage systems, information and communication technologies (ICT), advanced controls, etc. are used. In this way, DG penetration ratios are increased by distribution net-works that effectively monitored and controlled.

2.1 Objectives

The purpose of this project is to develop a coordinated voltage control method which ensures the voltage stability of a microgrid that contain wind and solar power systems. A microgrid model was installed in real time digital simulator system. Simulation model was controlled by fuzzy logic-based controller. Designed fuzzy logic-based voltage control system improved the voltage stability of the network system. Simulation results were obtained for different load and DG conditions and results were compared with uncontrolled system. Additionally, this project helps to develop their real time digital simulation software and hardware experiences of users.

2.2 Scope

In this project, a microgrid model that consist of seven buses system, a wind power system, a PV power system, an OLTC (On Load Tap Changer) controlled main power transformer and different loads is installed in real time digital simulation software (RSCAD). All of the buses voltages were measured by phasor measurement units (PMU) and this data were transferred to MATLAB/Simulink software. Designed fuzzy Logic based voltage-controlled system was also modelled in MATLAB/Simulink software. Matlab/Simulink and RSCAD software had online communication system. Voltage data of each bus bar were measured and transmitted to fuzzy logic controller in MATLAB. Fuzzy logic based controller had three outputs and these were on load tap changer (OLTC), power factor control and power curtailment control of DGs. Designed fuzzy logic-based voltage control system decided which control method was appropriate for the system before controlling it. Control signals were transmitted to OLTC system of main transformer, PV and Wind distributed generation systems by fuzzy logic controller. Thus, voltage of microgrid was controlled and stabilised by fuzzy logic-based controller. The simulation results obtained different load and DG power cases.

3 State-of-Technology

This project is focused on the performance of microgrid with PV and wind power integrated under effect of fuzzy coordinated voltage control. The DG based production is very crucial for microgrids since DERs are usually the main supplier of them. Therefore, in order to ensure the microgrid's stability and reliability in the short or the long run the use of voltage control strategies is of utmost importance. Also, the impact of the DGs power and loads voltage on a distribution grid play a crucial role to the selection of the control strategies. Since this project aims to investigate the effects of the DGs' output power and loads voltages in terms of microgrid stability and reliability. The performance of the fuzzy coordinated voltage control algorithm in terms of voltage stability improved with power factor correction, on load tap changer and power curtailment. The performance of the control algorithm tests under several different buses(loads) voltage and DGs' output power. The different conditions for tests are listed below:
For voltage

- Low voltage
- Medium voltage
- High voltage
- Very high voltage

For power

- Low power
- Medium power
- High power

The microgrid with PV and wind power implemented in RSCAD. The control algorithm implemented in Matlab/Simulink. The RSCAD and Matlab/Simulink communicated each other for data transfer by help of GTNETx2 board via TCP/IP protocol. The microgrid that implemented in RSCAD consists of PV, Wind DGs, variable loads, OLTC transformer, capacitors block for power factor corrections and control for wind power curtailment. In addition, it includes PMU block for measurement and GTNETx2 block for data transfer between RSCAD and Matlab/Simulink. On the other hand, Matlab/Simulink includes TCP/IP send and TCP/IP receiver blocks. The TCP/IP receiver block has a soft connection with RSCAD GTNETx2 block and the output of TCP/IP block is connected to the input of fuzzy coordinated voltage control block. The output of fuzzy coordinated voltage control block is connected to TCP/IP send block which also has soft connection with RSCAD GTNETx2 block.

4 Executed Tests and Experiments

During the activity the following tests were executed: The first a microgrid with 1.74MW PV system and 2MW Double Fed Induction Generator (DFIG) wind system was created in RSCAD. The implementation of microgrid in RSCAD is shown in Figure 1. It also includes an OLCT transformer. This test aims to measure the buses voltages and DGs' output power. Following this analysis, the researchers used the measured buses voltages and DGs' output power for Power Factor Control (PFC), On Load Tap Changers (OLTC) control and Power Curtailment (PC) control.

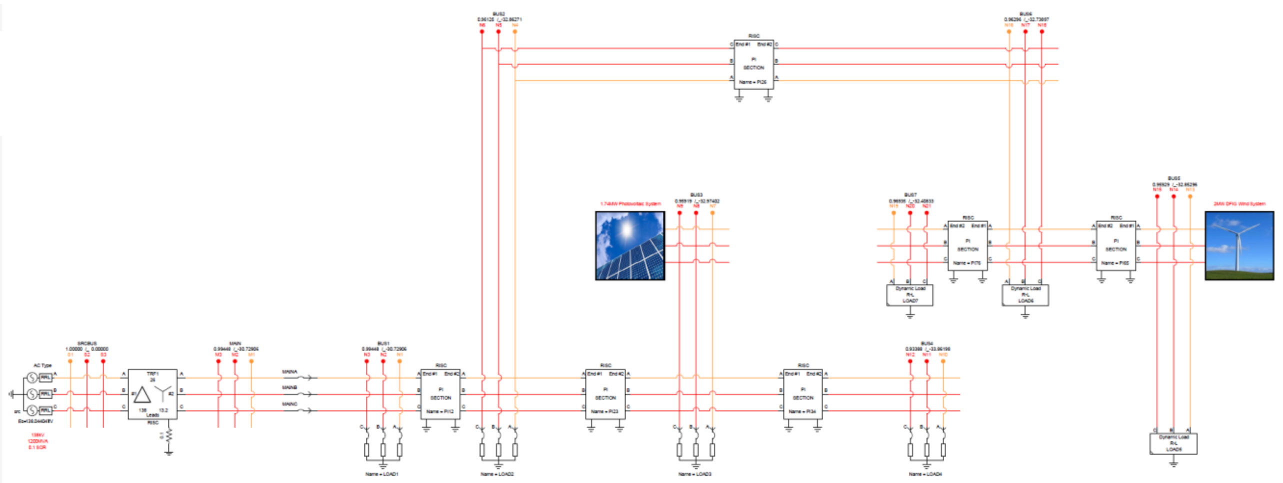


Figure 1 The implementation of microgrid in RSCAD

More analytically, in the test microgrid, PFC, OLTC and PC controls were implemented in RSCAD. On the other hand, a fuzzy control algorithm was implemented in Matlab/Simulink. By help of TCP/IP protocol Matlab/Simulink and RSCAD communicated each other. All these were analytically presented in section 4.3.

The measured quantities such as buses voltage and DGs' output power obtain from RSCAD environment and then transferred to Matlab/Simulink environment via TCP/IP protocol simultaneously. Voltage coordinate controller was implemented as Fuzzy Logic Controller (FLC). The transferred quantities were used as control input for FLC in Matlab/Simulink. The outputs of FLC were sent to RSCAD as inputs of PFC, OLTC controller and PC controller.

4.1 Test Plan

The first part of TA was dedicated to create following cases for FLC inputs in Matlab/Simulink. For the buses voltage V_LOW, V_MEDIUM, V_HIGH and V_VERY-HIGH were created. On the other for DGs’ output power P_LOW, P_MEDIUM and P_HIGH cases were created.

Cases for buses voltage:

1) Low: 0.9pu<V<0.95pu
2) Medium: 0.95pu<V<1.05pu
3) High:1.050pu<V<1.070pu
4) Very High: 1.070pu<V<1.10pu

Cases for DGs’ output power:

1) Low 1.5MW<DGs’ power< 2.3
2) Medium 2MW<DGs’ power< 2.8
3) High 2.5MW<DGs’ power< 3.5MW

In each cases obtained quantities were sampled with a resolution of 60 sample/second and then transferred to Matlab/Simulink environment as FLC’s inputs. In each cases simulations run for 2 minutes. Following quantities were obtained from the output of FLC controls: first one was for PFC, second one was for OLTC controller and the third one belonged to PC controller.

Finally, it is worth noting that during the 4 weeks of the activity the three experiments were not conducted in a specific order but their execution depended on the availability of the infrastructure and modifications in the various models.

4.2 Standards, Procedures, and Methodology

For setting up the various model components the following methodology and procedures were used:
Power Factor Correction: Figure 2 shows the single-line diagram of a power system. θ is the angle between real axis (I_{Re}) and imaginary axis (I_{Im}) of load current so $cos\theta$ is power factor that is equal to:

$$\cos\theta = {}^{P_L}/_{S_L} \tag{1}$$

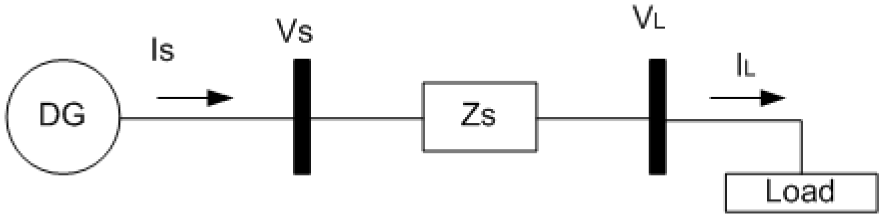


Figure 2 Simple scheme of Power system

where P_L and S_L are real and apparent power of load, respectively. By using reactive power compensator in load bus, the required reactive power is provided locally and the following equations are achievable:

$$I_L = I_s + I_{cp} = V_L(G_L + jB_L) - jV_L B_{cp} \, , Q_{cp} = -k_{cp} Q_L \tag{2}$$

where I_{cp} is the injected current by compensator, Q_{cp} is reactive power injected by compensator for power factor correction and the coefficient k_{cp} is compensation gain varying between zero and one. Thus, for complete compensation (k_{cp} =1):

$$I_{cp} = -I_{\iota m}\, , Q_{cp} = -Q_L \tag{3}$$

meaning that reactive power is completely supported by compensator. Note that depending on the closeness of k_{cp} to one, fewer capacity of DG is occupied and DG will be able to support additional loads. In addition, k_{cp} can be tuned based on load susceptance variation.

$$Q_L = S_L \sin\theta = S_L\sqrt{1-\cos^2\theta} = S_L\sqrt{1-(p.f)^2} \tag{4}$$

Voltage regulation can be defined as regulating DG output voltage based on load changes (for example, no load to full load). Similar to power factor analysis, Eq. (4) can be easily deduced as voltage deviation at load bus:

$$\Delta V = Z_S I_L = \frac{R_S P_L + X_S Q_L}{V_L} + j\,\frac{X_S P_L - R_S Q_L}{V_L} \tag{5}$$

Where

$$Z_s = R_s + jX_s \tag{6}$$

It is clear that voltage deviation is dependent on both real and reactive power consumption of load. Since compensator is added to the system (in parallel with load), it tries to reduce voltage deviation ($\Delta V \rightarrow 0$).

On Load Tap Changer (OLTC): Once the limitation of the power factor control or reactive power capability has been reached, the OLTC control option should be chosen to further help maintain the voltages within its permissible limits. The typical values of the lower limit of the dead band of the OLTC range from 0.85p.u. to 0.90p.u., whereas those of the upper limit usually range from 1.10p.u. to 1.15p.u. Several works which have been carried out in different countries and environment have found that setting the OLTC set point in the range of 1.015p.u. to approximately 1. 033p.u was found to be effective in managing voltage fluctuations and in limiting network losses in the study. In the simulation work performed, two different settings of OLTC of Vmax = 1.05p.u. and Vmin = 1.02p.u. are used where the latter was found to be more effective in managing higher levels of voltage than the setting of 1.05p.u.

DG Power Curtailment: The lowest priority or the least preferred option of control is the curtailment control since there are various factors that need to be taken into consideration. This method is mostly implemented to tackle voltage rise as a last resort when the generators have exhausted their capability of voltage control. This method the only way to stay within statutory voltage limits when there are limits to the amount of reactive power that can be absorbed or injected and curtailment. Wind energy curtailment is the most frequent energy curtailed involving DGs. Several countries which practice this wind energy curtailment include the United States as well as Canada, Germany, New Zealand, Ireland, and Spain. In this study we used a microgrid with 2 MW of DG, it is suggested that 41% of the active power must be curtailed to manage voltage rise. However, the reasonability of the percentage of curtailment must also depend on the duration of the curtailment.

Designed Coordinated Fuzzy Logic Voltage Control System: In this study we designed a microgrid with 1.74MW PV system and 2MW wind system. Simulations were carried out by using the RSCAD environment. For the simulation DGs were connected to at two of the buses. That is shown in Figure 3.

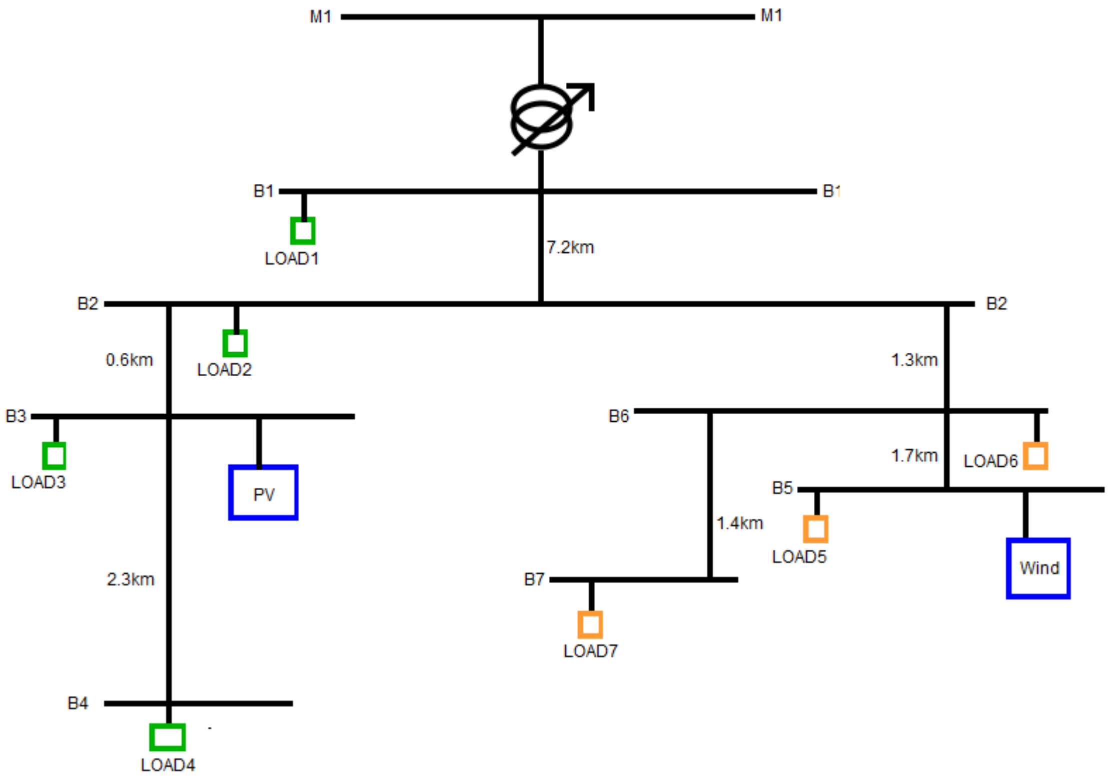


Figure 3 Microgrid for test case

Figure 4 shows the implementation of the coordinated fuzzy logic voltage control for a distribution network connected with DGs. Initially the voltage is checked at each load buses of the network. If the voltage limits are violated at any nodes, fuzzy logic actions will be taken according to the algorithm of control. It decides from which of the three modules, the power factor control, the on load tap changer and the generation curtailment control to be activated and applied when voltage is detected not to be within its permissible limits. If the chosen control option was not able to handle the voltage any longer, it was decided from the fuzzy logic controller to determine which control option was to be activated.

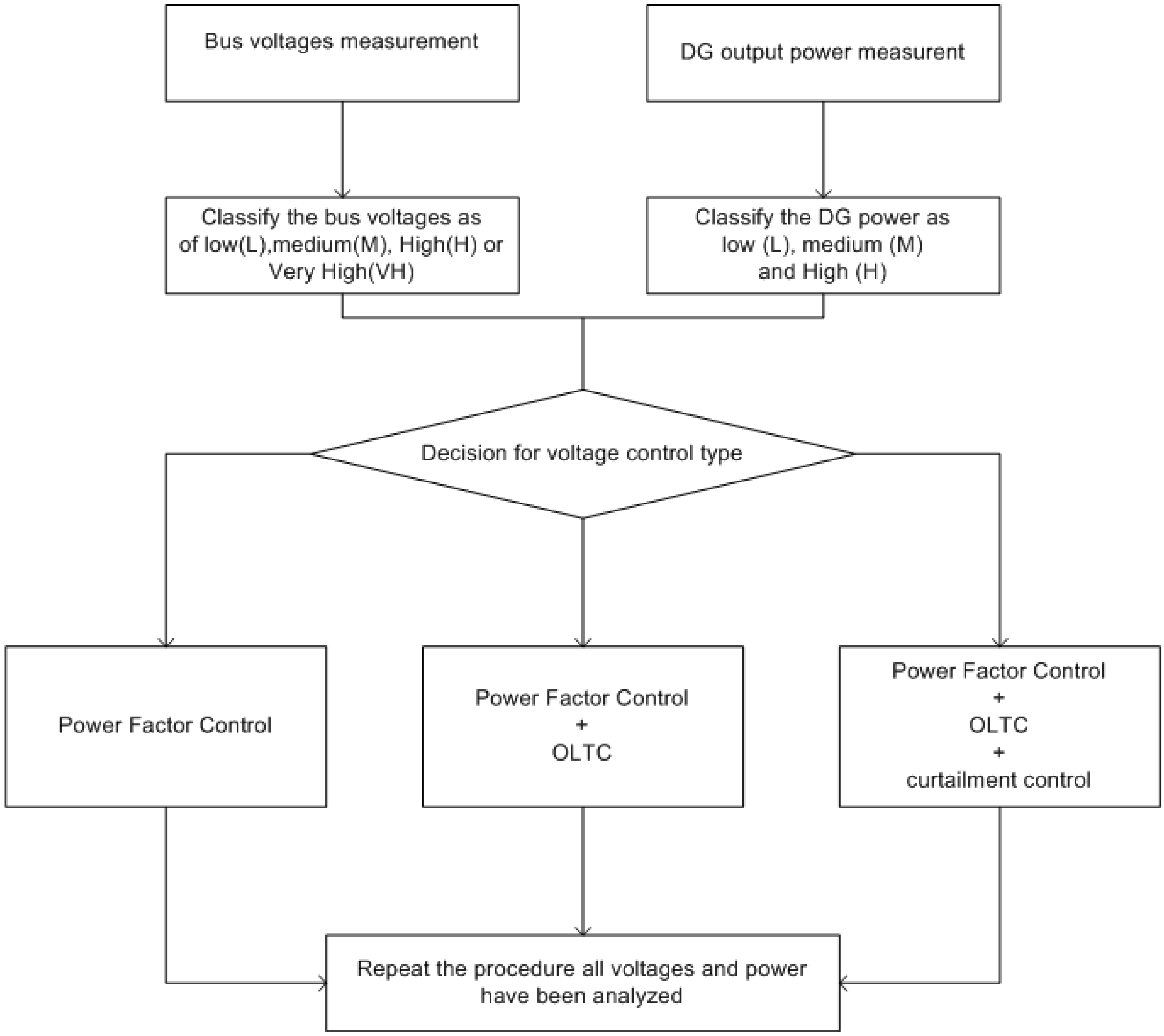


Figure 4 Decision Algorithm of controller

Fuzzy Logic Control System: Fuzzy Logic Control (FLC) uses the principles of fuzzy logic-based decision making to arrive at the control actions. In essence, some measurements (e.g. output measurements) from the system to be controlled are matched with a knowledge base of control for a particular system. By selecting suitable input-output linguistic variables utilizing rule base, a wide range of desirable control outcomes can be realized. A fuzzy rule is generally a linguistic relation of the form.

Fuzzy logic controllers consist of a set of linguistic control rules based on fuzzy implications and the rules of inference. A fuzzy knowledge base (offline) must first be developed before following these steps in developing a fuzzy logic control.

1- Develop a set of linguistic control rules (protocols) that contain fuzzy variables as conditions (process outputs) and actions (control inputs to the process).
2- Obtain a set of membership functions for process output variables and control input variables.
3- Use the ‘fuzzy AND’ operation and the fuzzy implication operation on each rule in Step 1. Obtain the multivariable rule base for that rule as in Step 2.
4- Combine the relations using the fuzzy connectives ‘fuzzy OR’ or ‘to obtain the overall fuzzy rule base relationship.

To obtain a single crisp solution for the output variable, a fuzzy system aggregates all output fuzzy sets into a single output fuzzy set, and then defuzzifies the resulting fuzzy set into a single number. This process is known as fuzzy inference and is one of the most famous applications of fuzzy logic and fuzzy sets theory.

Fuzzy inference can be defined as a process of mapping from a given input and an output, using the theory of fuzzy sets. The fuzzy inference process includes four steps: fuzzification of the input variables, rule evaluation, aggregation of the rule outputs and defuzzification. Fuzzification is the first step where the crisp inputs are taken and the degrees to which the inputs belong to each of the appropriate fuzzy sets are determined. The rules are evaluated using appropriate fuzzy operator (AND or OR) to obtain a single number that represents the result. Aggregation is the process of unification of the outputs of all the rules. The defuzzification process which utilizes the aggregated output of fuzzy set to produce a single output is the final step done in this method. Two fuzzy inference techniques are the Mamdani and Sugeno methods. The Mamdani method is widely accepted in fuzzy expert systems for its ability to capture expert knowledge in fuzzy rules. However, the Mamdani method would cause computational burden. On the other hand, the Sugeno method improves the computational efficiency of the fuzzy inference and it also works well with adaptive and optimization techniques, which makes it very suitable choice for control of a dynamic non-linear systems. It is a must to tune the fuzzy logic system which has been developed by adjusting the specific fuzzy sets and fuzzy rules to meet specified requirements desired.

<u>Fuzzy Logic Control Inputs Membership Functions</u>: For this case study, the inputs to the system identified were the load voltages and DG input power. Here, the voltages which act as input to the system were classified into 4 different membership functions which are shown in Figures 5. Low, High and Very High membership functions of voltages were triangular, Medium membership function of voltages was trapezoidal.
Limit for buses voltage membership functions :

1- Low = 0.900p.u ≤ V ≤ 0.950p.u
2- Medium = 0.950p.u ≤ V ≤ 1.050p.u
3- High = 1.050p.u ≤ V ≤ 1.070p.u
4- Very High = 1.070p.u ≤ V ≤ 1.100p.u

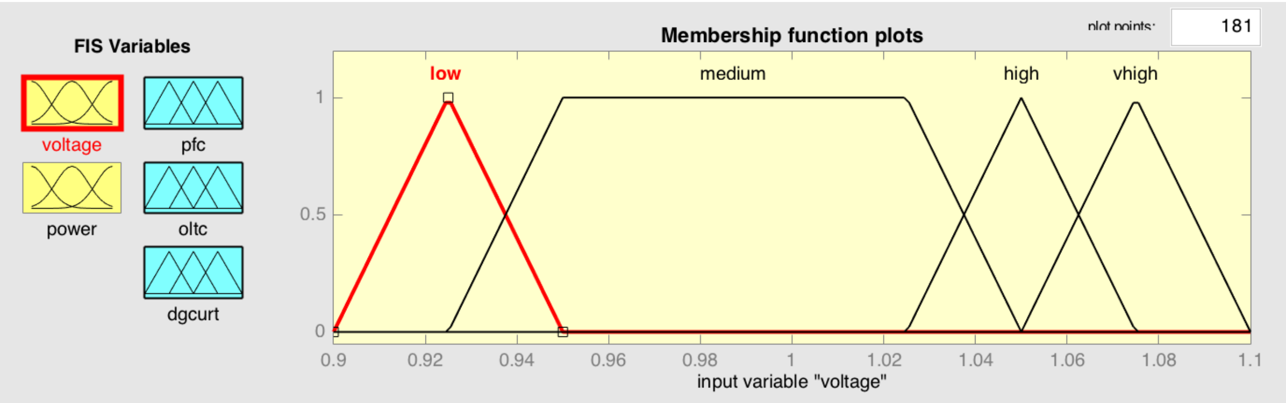


Figure 5 Input voltage membership functions

The second input to the system was the DG input power which was consist of three membership functions. These membership functions are shown in Figure 6. All of the membership functions were triangular.

Limit for DGs'output power membership functions:

1) Low 1.5MW<DGs' power< 2.3
2) Medium 2MW<DGs' power< 2.8
3) High 2.5MW<DGs' power< 3.5MW

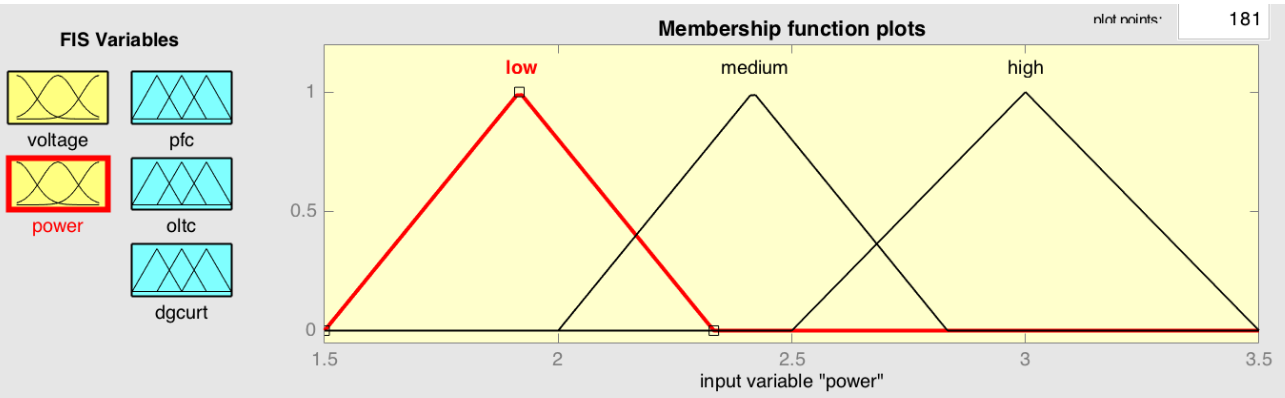


Figure 6 DG output power input membership functions

<u>Fuzzy Logic Control Output Membership Functions</u>: The membership functions for the outputs of the fuzzy logic control system developed were identified as the voltage control options to be activated when different ranges of input voltages and different DG input power were being fed into the system. The output control options were basically classified into 3 different categories, the PFC, the OLTC control, and the generation curtailment control. The power factor control option was firstly implemented and chosen. This is due to the fact that the generator is operating at certain power factor and has its own reactive power capability. PFC indicates the reactive power output of the generating unit maintained in proportion to the real power (MW) output such that the power factor remains constant. The reactive capability of a typical generator at a full load normally ranges between 0.85 lagging and 0.95 leading. Operating the DG in leading power factor specifically was found to mitigate the voltage rise issues.

On the other hand, operating the DG at lagging power factor will increase the voltage level at the load buses and therefore is suitable for managing the lower voltage. Two operating power factor control of 0.90 and 0.95 leading are activated where the PFC at 0.95 leading is found to be suitable in the medium range of permissible voltage limits of ±5% (between 0.95 and 1.05p.u.). For voltages in the range of high and very high range, power factor of 0.90 leading is used for control. Figure 7 depicts the output membership functions of this first control option which is categorized into 3 triangular membership functions.

Limit for PFC membership functions:

1- 0.85 lagging 0.9<Q/P ratio< 0.95
2- 0.95 leading 0.92<Q/P ratio<1.05
3- 0.90 leading 1<Q/P ratio<1.1

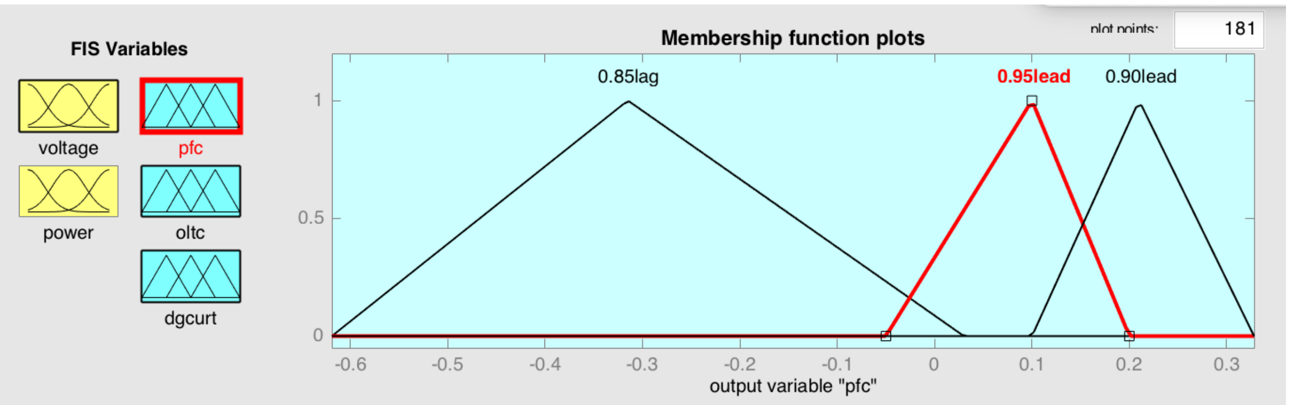


Figure 7 Power Factor Control (PFC) membership functions

Once the limitation of the power factor control or reactive power capability has been reached, the OLTC control option should be chosen maintain the voltages within its permissible limits. The typical values of the lower limit of the dead band of the OLTC range from 0.85p.u. to 0.90p.u., whereas those of the upper limit usually range from 1.10p.u. to 1.15p.u. Several works which have been carried out in different countries and environment have found that setting the OLTC set point in the range of 1.015p.u. to approximately 1.033p.u was found to be effective in managing voltage fluctuations and in limiting network losses in the study. In the simulation work performed, two different settings of OLTC of Vmax = 1.05p.u. and Vmax = 1.02p.u. were used where the latter was found to be more effective in managing higher levels of voltage than the setting of 1.02p.u. in managing the voltage rise in the system. Therefore, in the implementation, this second control option in priority shown in Figure 8 is categorized into two different membership functions. 1.02pu membership function was chosen trapezoidal and 1.05pu membership function was chosen triangular.

Limit for OLTC membership functions:

1- 1.02p.u 0.95<Voltage<1.06
2- 1.05p.u 1<Voltage<1.1

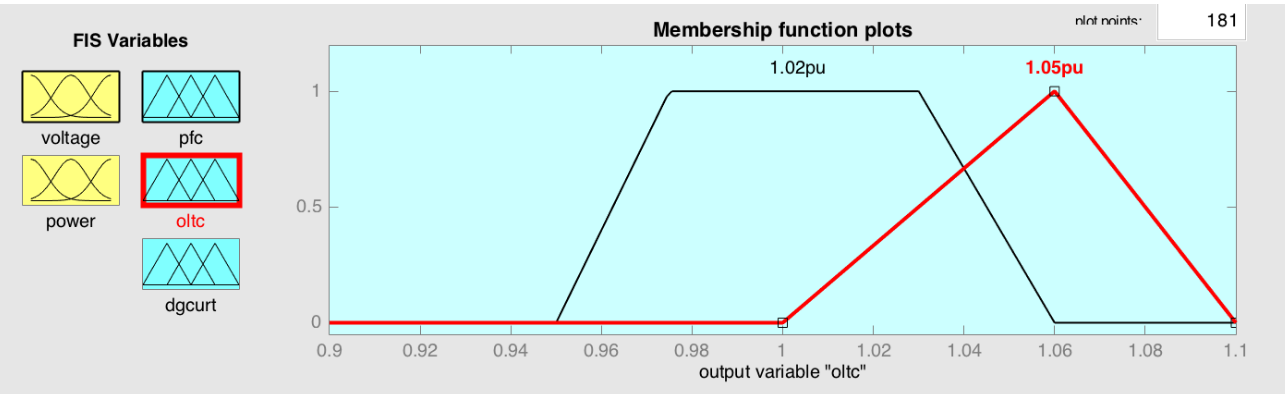


Figure 8 On Load Tap Changer (OLTC) membership functions

The lowest priority or the least preferred option of control is the curtailment control since there are various factors that need to be taken into consideration. Wind energy curtailment is the most frequent energy curtailed involving DGs. Several countries which practice this wind energy curtailment include the United States as well as Canada, Germany, New Zealand, Ireland, and Spain. In this study we used a simple seven-bus system with 3 MW of DG, it is suggested that 41% of the active power must be curtailed to manage voltage rise. However, the reasonability of the percentage of curtailment must also depend on the duration of the curtailment. DG curtailment control is third fuzzy controller’s output and shown in Figure 9. The membership functions were categorized into two different membership functions. 0pct membership function was chosen trapezoidal shape and 40pct membership functions was chosen as triangular.

Limit for DGC membership functions:

1- 0% curtailment 0.9<curtailment ratio<1.04
2- 40% curtailment 1<curtailment ratio<1.1

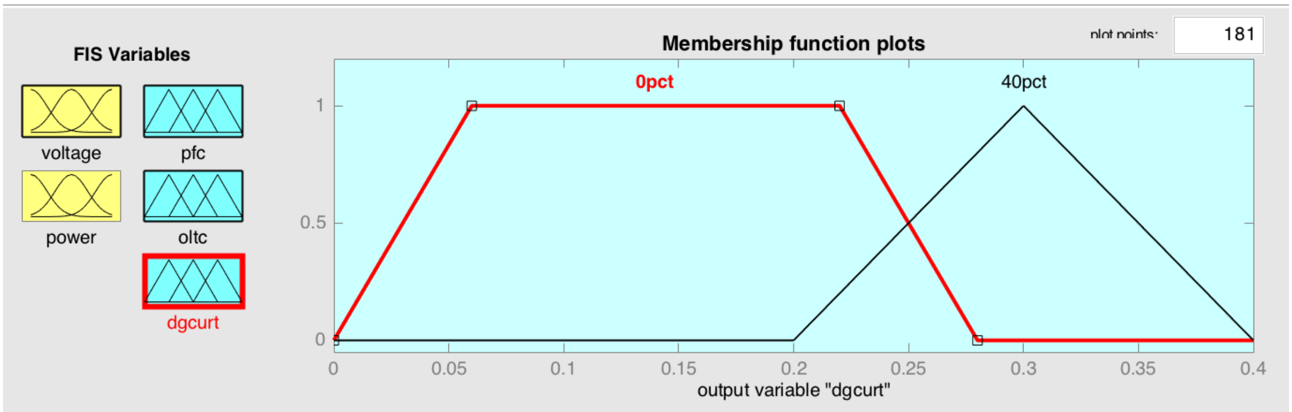


Figure 9 DG Curtailment control membership functions

Fuzzy Logic Control Rules: The fuzzy control system was developed using two inputs and three outputs with the outputs further detailed into different operating options. Some of the examples of the generated rules for the fuzzy logic control system are as follows with Figure 10 illustrating the control rules captured from the program developed.

I. If voltage is low and power is low, then pfc 0.85 lag
II. If voltage is medium and power is high, then pfc 0.95lead
III. If voltage is high and power is medium, then pfc 0.90 lead, OLTC 1.02 p.u, gencurt 0%
IV. If voltage is very high and power is very high, then pfc 0.90 lead, OLTC 1.02 p.u and gencurt 40%.

In the fuzzy logic controller, min was selected as AND method, max was selected OR method, min was selected for implication, max was selected for aggregation and centroid was selected as defuzzification method.

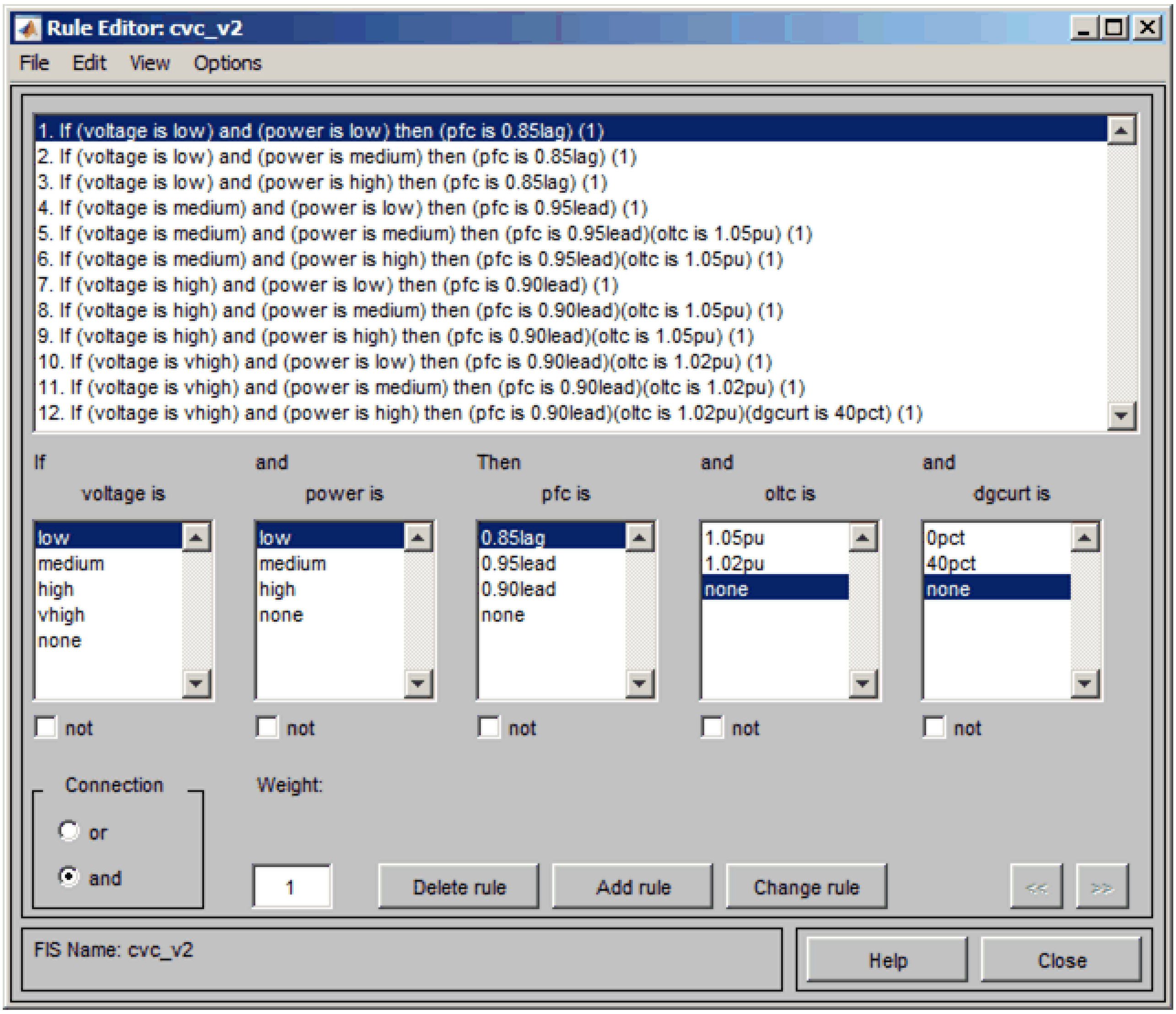


Figure 10 FLC rules table

4.3 Test Set-up(s)

The diagram of Figure 11 provides an illustration of the physical connection equipment for experiment. We used GTNETx2 SKT board for experiment setup. It is deployed to measure three phase instantaneous values of voltage and current. GTNETx2-SKT board is WAN network through Ethernet cable.

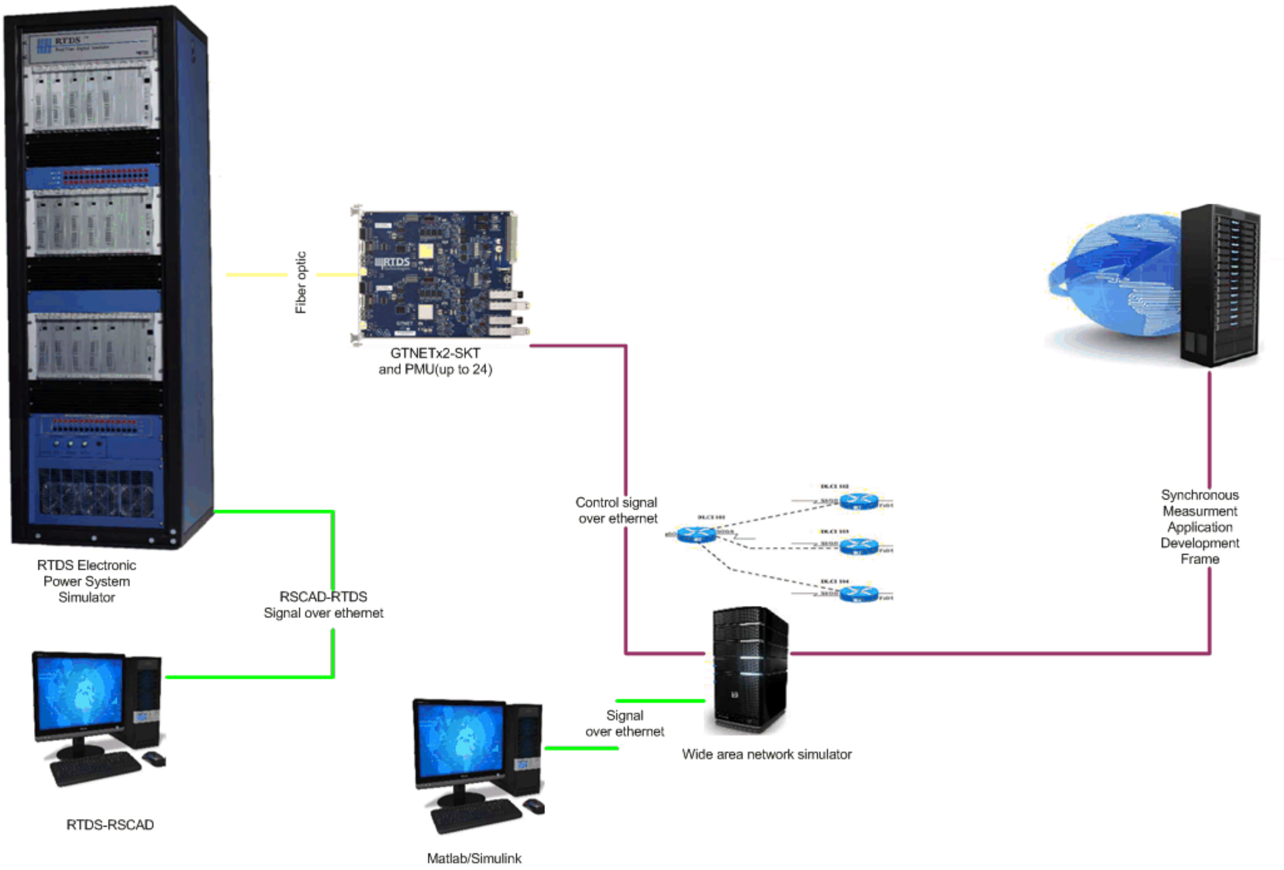


Figure 11 Physical experimental setup

In addition to the above generic diagram, the corresponding RSCAD, Matlab/Simulink implementation is shown in Figure 12.

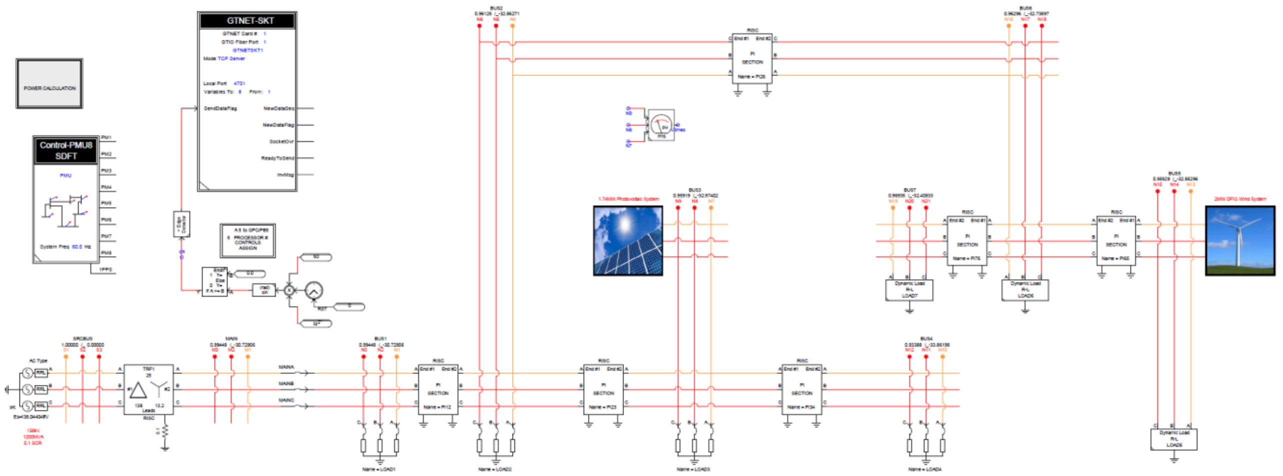


Figure 12 Corresponding RSCAD model with GTNETx2-SKT board

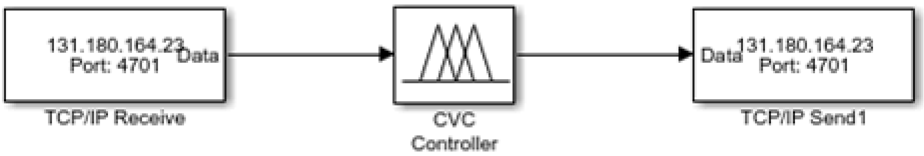


Figure 13 Corresponding Matlab/Simulink Model for TCP/IP configuration with GTNETx2-SKT board

The GTNETx2-SKT and Matlab/Simulink were communicated over Ethernet via TCP/IP protocol (Figure 13). In this study GTNETx2-SKT board configured as server and Matlab/Simulink as client. Also, apart from the complete implementation model, GTNETx2-SKT RSCAD model of the implementation and GTNETx2-SKT configuration are depicted in the following figures: Figure 14 illustrates the RSCAD model for GTNET-SKT and PMU, Figure 15 shows the configuration menu for GTNERx2-SKT backbone software connection and TCP/IP sets, Figure 16 shows the TCP/IP protocol configuration for GTNETx2-SKT board. In addition, Figure 17 and 18 show configuration for Matlab/Simulink send and receive block and Figure 19 shows Matlab/Simulink configuration parameters.

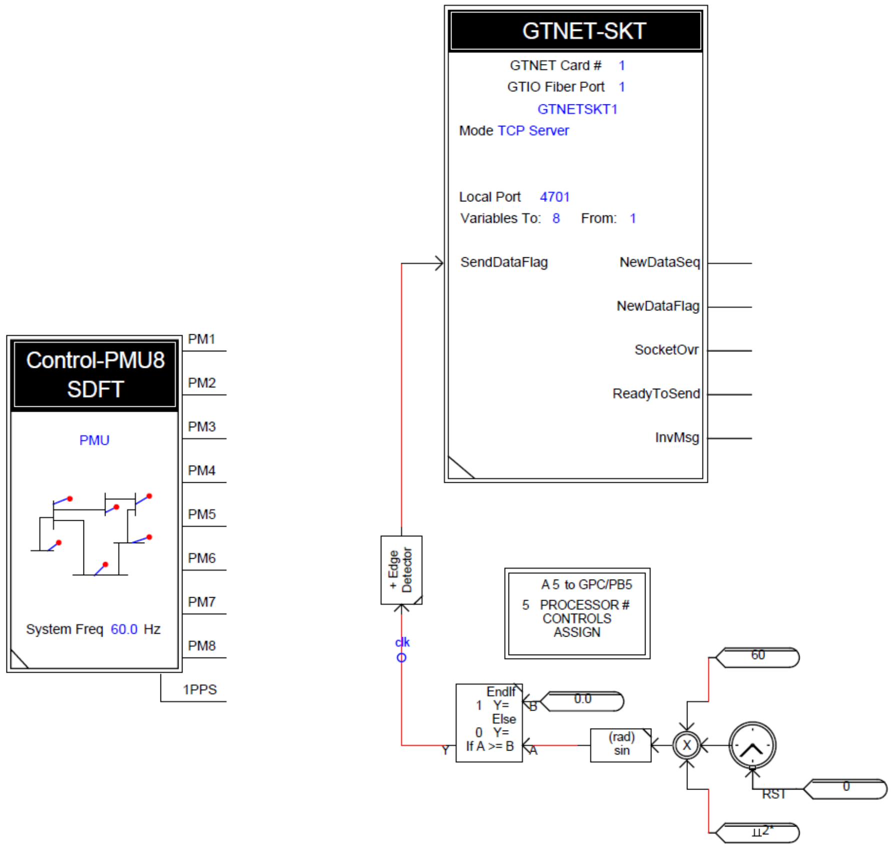


Figure 14 RSCAD model for PMU and GTNET-SKT blocks

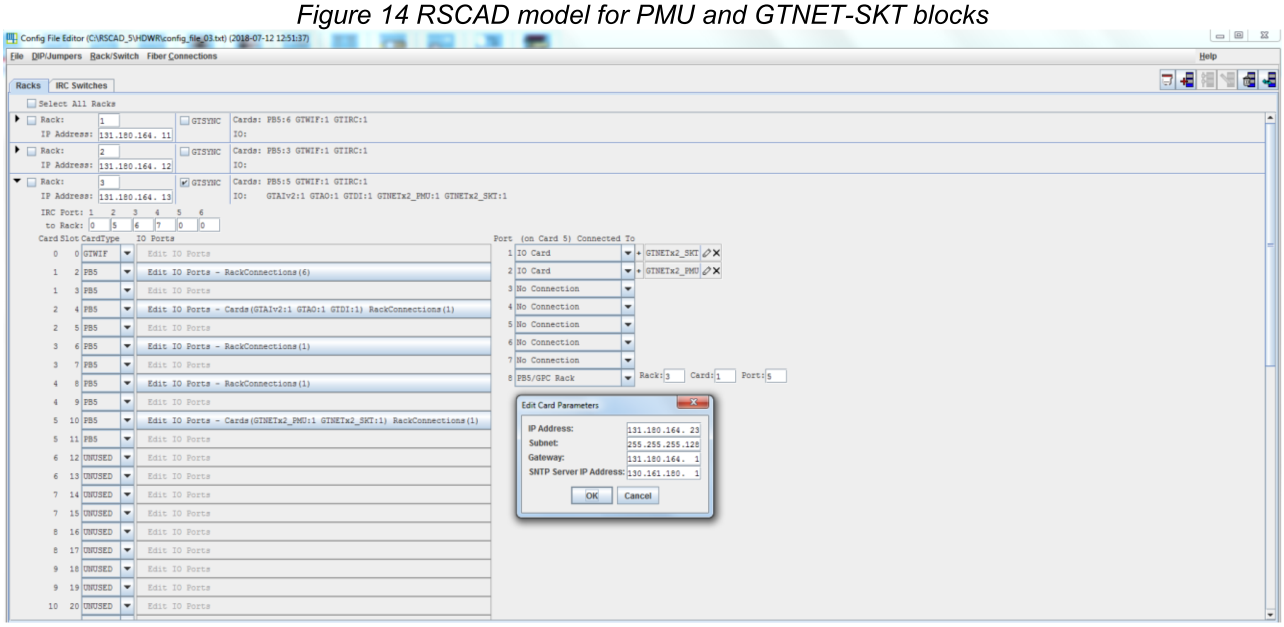


Figure 15 GTNETx2-SKT board backbone software connections and TCP/IP sets

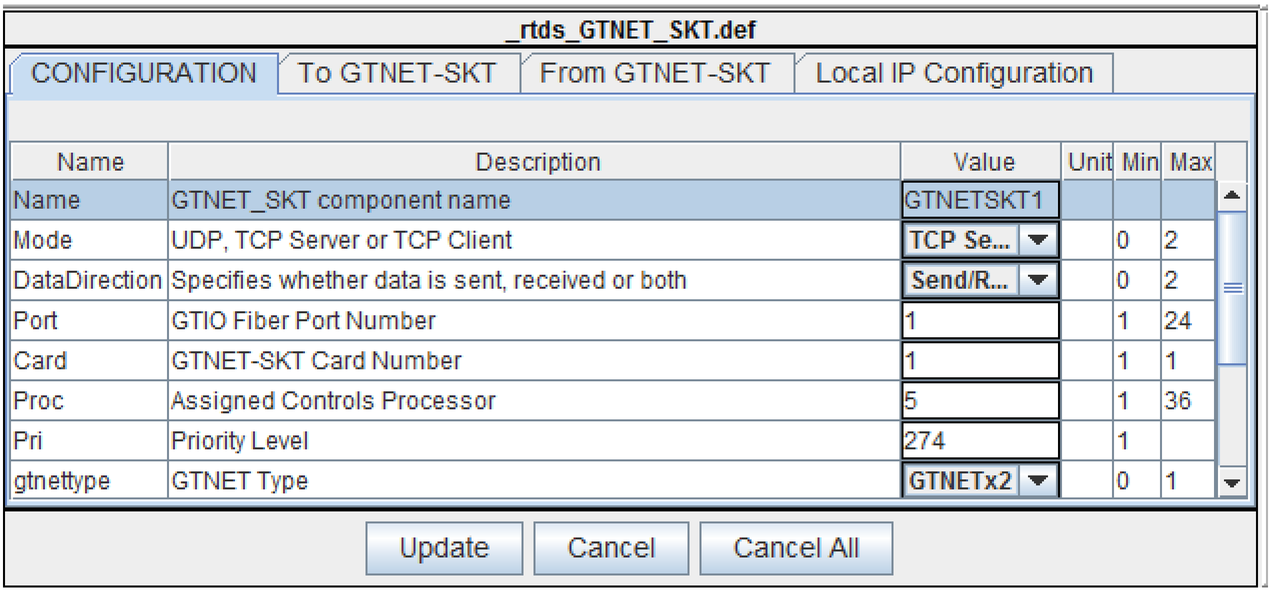


Figure 16 GTNETx2-TCP/IP configuration

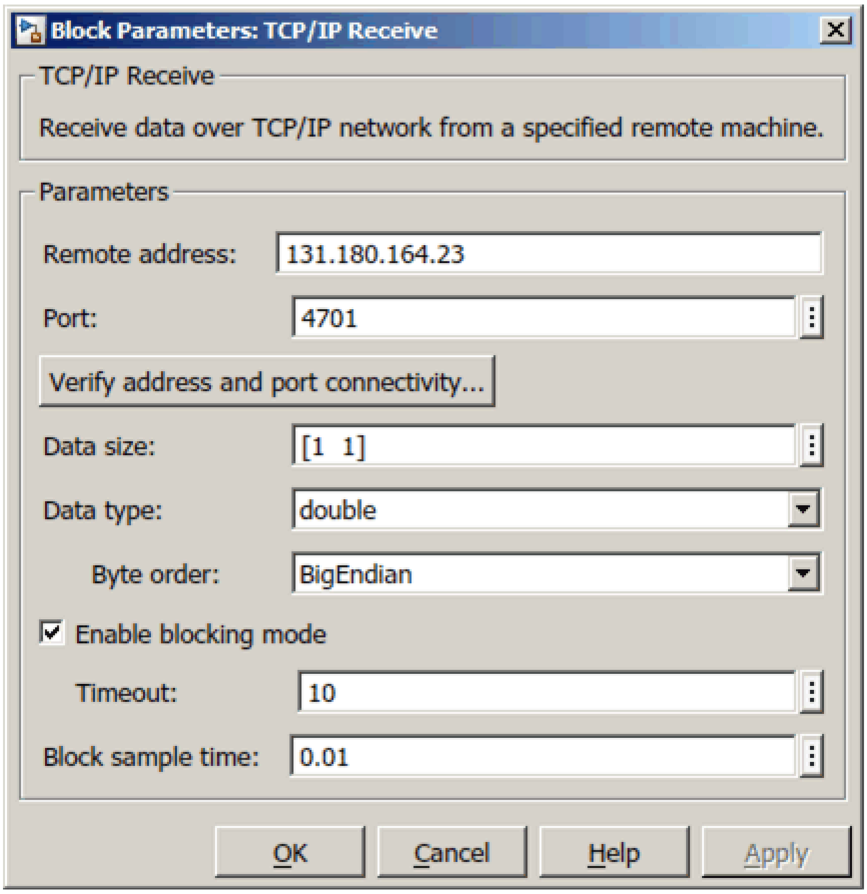


Figure 17 Configuration for Receive block of Matlab/Simulink

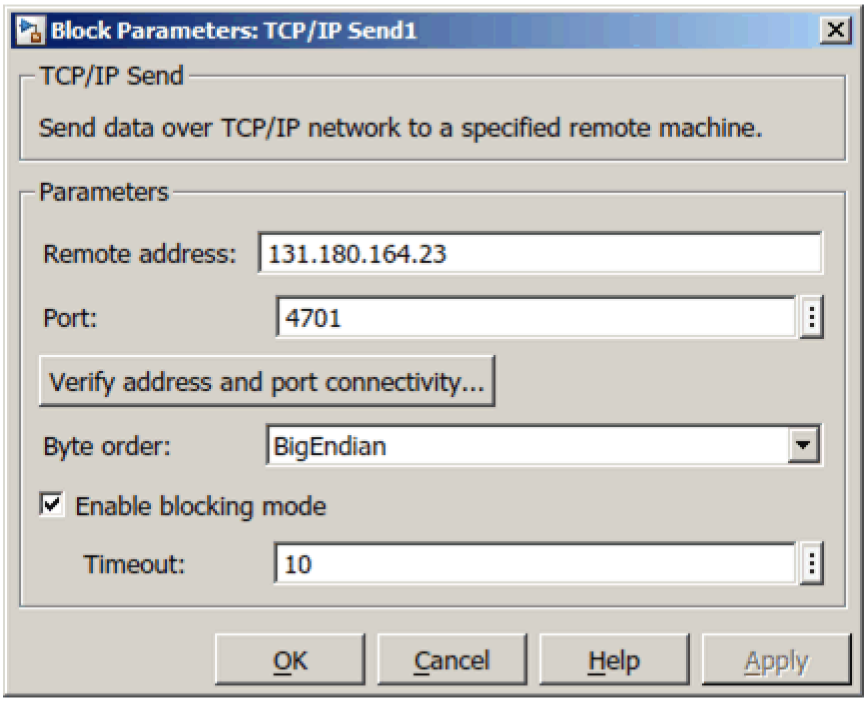


Figure 18 Configuration for send block of Matlab/Simulink

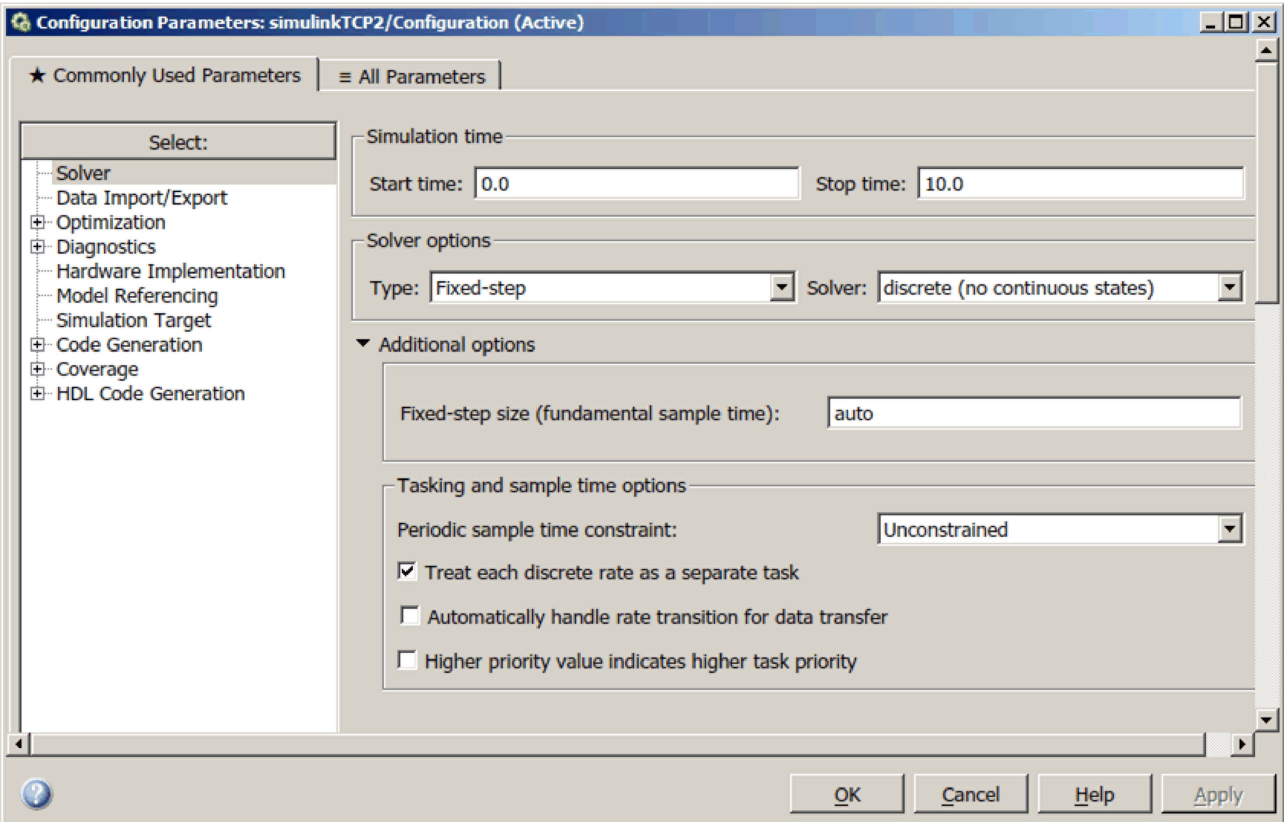


Figure 19 Configuration for simulation of Matlab/Simulink

The overall system topology with controller is shown in Figure 20. The loads (buses) voltage and DGs' output power get from PMU unit. The sampling rate of PMU was set as 60 samples/second. The designed controller unit in Matlab/Simulink received via TCP/IP protocol. The controller decided suitable control mechanism listed as follow to keep voltage constant.

I. Voltage and power is low; apply PFC
II. Voltage is Medium and High and power Medium; apply PFC and OLTC
III. Voltage is V High and power High; apply PFC, OLTC and PC

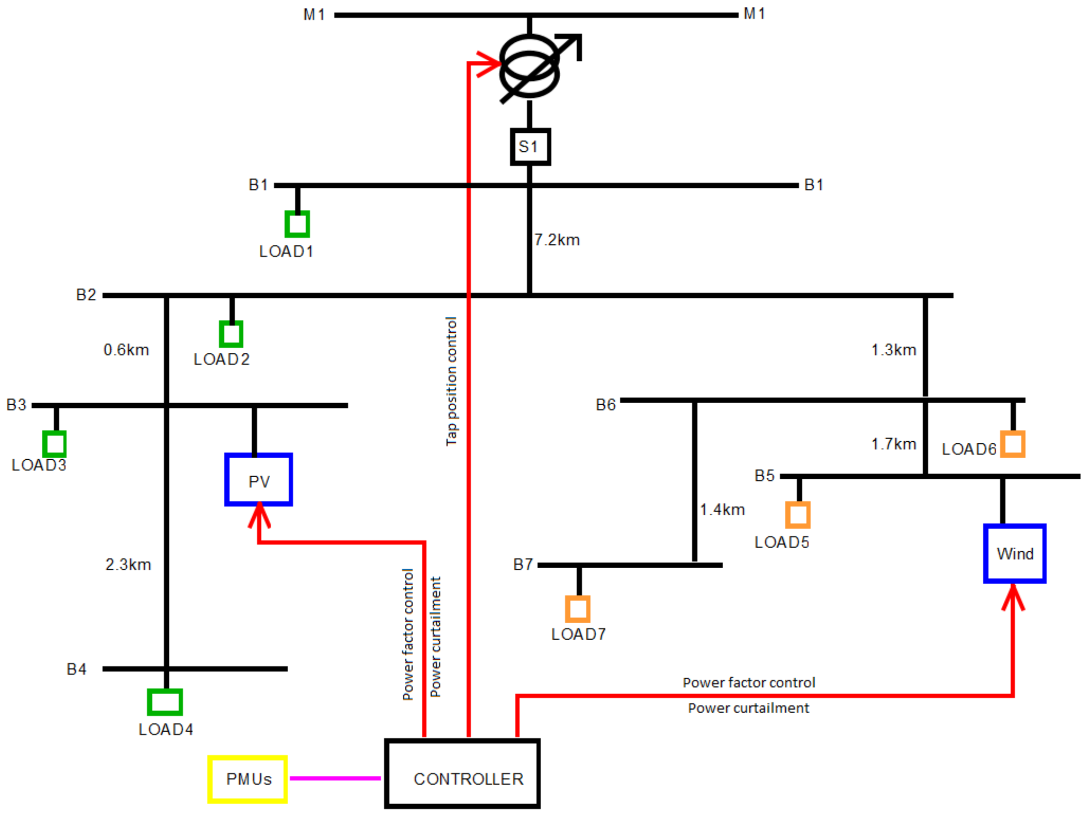


Figure 20 System topology with controller

4.4 Data Management and Processing

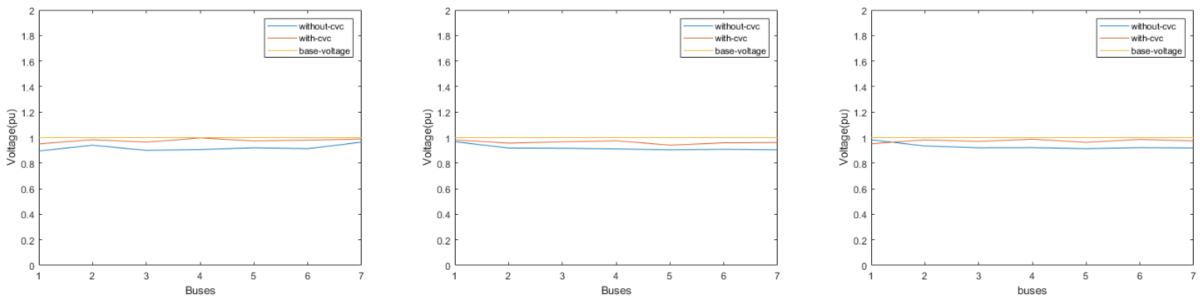
As it is shown above the input quantities such as loads voltages and DGs' output power were measured via GTNETx2-SKT and PMU units. TCP/IP protocol used to transmit data to Matlab/Simulink environment as controller inputs. The controller inputs save as load1_voltage.cvs, load2_voltage.cvs, load7_voltage.cvs and DG1_power.cvs, DG2_power.cvs. The controller outputs saved as PFC.cvs, OLTC.cvs and PC.cvs with a time resolution of 2 minutes. The output data can be further processed in Matlab or Excel.

5 Results and Conclusions

The objective of the implementation of the fuzzy logic coordinated control is to control the voltage at the load buses within its permissible limits. The performance of the control algorithm was investigated under various buses voltages and DGs's output power conditions. The conditions are listed in section 4.1 as below:

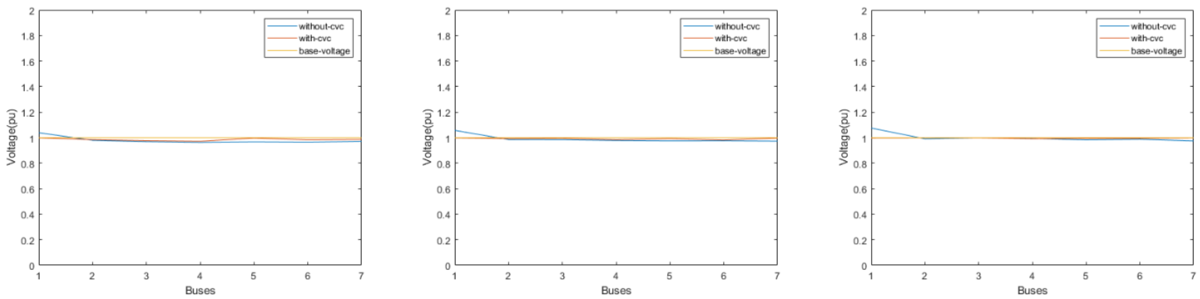
1) Low voltage, low power
2) Low voltage, medium power
3) Low voltage, high power
4) Medium voltage, low power
5) Medium voltage, medium power
6) Medium voltage, high power
7) High voltage, low power
8) High voltage, medium power
9) High voltage, high power
10) Very high voltage, low power
11) Very high voltage, medium power
12) Very high voltage, high power

For each conditions, buses voltage was recorded with and without controller. In each case recorded quantities were plotted and compared with base voltage case.



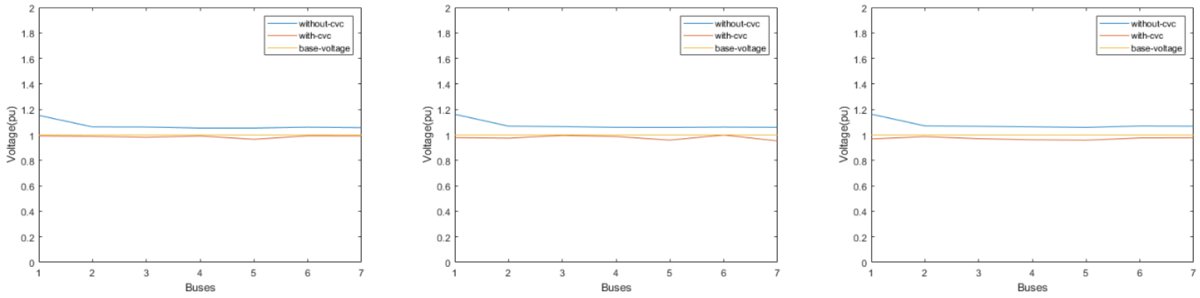
a) b) c)

Figure 21 Low buses voltage for a) low power b) medium power c) high power



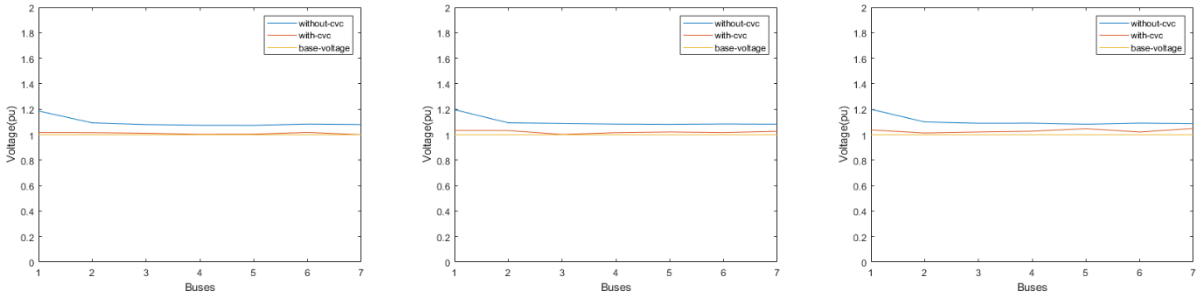
a) b) c)

Figure 22 Medium buses voltage for a) low power b) medium power c) high power



a) b) c)

Figure 23 High buses voltage for a) low power b) medium power c) high power



a) b) c)

Figure 24 Very High buses voltage for a) low power b) medium power c) high power

The performance of the system with CVC and without CVC were compared to base voltage case in terms of buses voltages. The analytical buses voltage for each case such as low voltage, medium voltage, high voltage and very high voltage is depicted in Figure 21, Figure 22, Figure 23, and Figure 24 respectively. Furthermore, each cases for buses voltage included also low, medium and high DGs' output power. The results of this comparison indicated that the CVC algorithm can significantly keep the buses voltage in an acceptable range for operation.

On the other hand, the results show that under different operating conditions, the buses voltages were still should be kept within its allowable limits of not more than 1. 05p.u.by the fuzzy logic coordinated voltage control. In addition, without using the fuzzy logic coordinated voltage control, the voltages at the buses were mostly outside the allowable maximum limit of 1.05p.u. By utilizing the fuzzy logic coordinated voltage control, the desired output voltage range of less than 1.05p.u are still managed to be achieved.

6 Open Issues and Suggestions for Improvements

In this project at TU Delft RTDS laboratory we had a digital real-time simulator(RTDS) for microgrid simulation and a software control(Matlab/Simulink). The whole tests were executed by Software In the Loop(SIL). From a technical point of view some of the potential improvements of the specific tests concern the following topics:

A Control Hardware In the Loop(CHIL) requires such main components, a real-time digital simulator(RTDS) for power system simulation, a hardware controller, that can control for a power component (e.g. inverter control, relay control, etc) or a centralized controller (e.g. distribution management system controller, microgrid controller). The advantages of CHIL testing compare to pure simulation or SIL, are significant. RTDS are able to solve the power system's mathematical equations in real-time (typical time-step are≤50μs), thus enabling the Smart Grid Control Algorithm (SGCA) to be implemented on a physical hardware controller, interfaced with RTDS a microgrid system can be investigate and control in real time and tested under realistic conditions. In addition, CHIL simulations can reveal “hidden” weaknesses of the control algorithms, and study their performance under various realistic conditions, such as time delays, noise, etc. However, since all of the network components are simulated, CHIL testing fails to represent the interaction of the hardware controller with physical power devices.

One of the future works can be arranged on fuzzy logic controller optimisation. Because of fuzzy system have uncertainty, users must make a lot of experiments in fuzzy sets. Due to time constraints, there are not adequate optimizations done in the fuzzy system. Fuzzy Logic controller can be optimized in the future works. Optimization may contribute to better control results for microgrid system.

7 Dissemination Planning

It is planned to submit one paper for conference. It will be submitted to “2019 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)”.

8 References

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9 Annex

9.1 List of Figures