Eksplorium *p*-ISSN 0854-1418
Volume 45 No. 2, November 2024: 132–144 *e*-ISSN 2503-426X

Microgrid Stability Margin Enhancement Strategy in Different Operating Conditions by Using Design of Supplementary Damping Controllers in the Most Effective Microgrid VSC

Meysam Yousefi[1], Mahmoud Zadehbagheri[2*], Samad Nejatian[3], Mohammad Javad Kiani[4]

[1]Department of Electrical Engineering, Yas.C., Islamic Azad University, Yasuj, Iran.

[2]Department of Electrical Engineering, Yas.C., Islamic Azad University, Yasuj, Iran (Corresponding Author).

Email: mzadehbagheri@iau.ac.ir

[3]Department of Electrical Engineering, Yas.C., Islamic Azad University, Yasuj, Iran.

[4]Department of Electrical Engineering, Yas.C., Islamic Azad University, Yasuj, Iran.

Article Received: 18 Sept 2024, Revised: 29 Oct 2024, Accepted: 10 Nov 2024

Abstract

Energy systems have received widespread attention due to their importance in our daily lives. Most of our energy generation systems are based on fossil fuels, which are non-renewable and are accompanied by unavoidable hazardous carbon emissions. The aim of the present study is to develop a strategy to enhance the stability margin of microgrids in different operating conditions by using design of supplementary damping controllers in the most effective microgrid VSC. The main objectives of this study are to investigate the dynamic behavior of the power system, which includes synchronous and asynchronous generators. For this purpose, two power sources, namely diesel generator and doubly fed wind turbine (DFIG), are considered, which are connected to the load by the transmission line. In order to investigate the dynamics of the system under disturbance conditions, various errors are also considered. Another important part includes the control system which is a combination of neural-fuzzy network (ANFIS) with current and voltage control inputs.

Keywords: Strategy, Microgrid Stability Margin, Complementary Damping Controllers, VSC

.1INTRODUCTION

The increasing carbon emission is very important in the intensification of global warming. There is an urgent need to limit this threatening phenomenon to prevent large-scale environmental disasters. These fossil fuels, including oil, coal and gas, are continuously decreasing at a dizzying rate, raising a red flag for concerned scientists to urgently deal with this issue [1]. Moreover, the global shortage of fossil fuels has consequently led to an excessive increase in its price [2]. According to experts, the widespread dependence on fossil fuels can significantly disrupt the development process of countries and sometimes become a cause of obvious economic stagnation that brings countries to the brink of complete failure. In the modern era, fossil fuel-powered vehicles are giving way to high-tech electric vehicles that are environmentally friendly with zero emissions. This rapid adaptation of electric vehicles bodes well for the environment and the automotive industry. Engineers have been working to charge these electric vehicles using cheaper and more efficient power supply sources.

In addition, scientists are conducting extensive research to understand alternative energy sources to eradicate carbon emissions and meet the energy needs around the world that are continuously increasing. Some of the issues related to the energy system include: fossil fuel depletion, relentless increase in greenhouse gas (GHG) emissions, and energy shortage [3]. It is a common belief among experts that significant use of renewable energy sources to meet the growing energy demand is the most suitable alternative available at present. In this regard, optimal energy management is essential to obtain maximum results from renewable resources, which can be achieved through microgrids. Microgrid is a decentralized and flexible energy system that facilitates the transition from fossil fuels to renewable energies. It integrates renewable resources such as solar and wind and reduces the dependence on centralized infrastructure. Microgrids increase grid flexibility, promote energy independence, and optimize management. The severe depletion of energy reserves requires the urgent development of energy management strategies to rectify such widespread concerns. The panacea for all these issues lies in the effective implementation of a microgrid energy management system [4]. The aim of the study is also to design a complementary adaptive neuro-fuzzy controller in AC microgrids with the aim of improving dynamic stability and improving the voltage profile in the grid.

.2PROBLEM STATEMENT AND RESEARCH NECESSITY

The term microgrid refers to a small-scale power generation and distribution system in which a set of loads is locally powered by several RES. RESs provide their generated electrical power to the loads through power electronic converters. In fact, microgrid is a new approach to increase local DERs based on renewable energies near load centers (electrical energy distribution). Although the ultimate goal of microgrids is to achieve 100% penetration of renewable energy sources in the distribution network, the use of some small-scale synchronous generators such as diesel generators as a type of distributed energy source is inevitable. The generation of electrical power in most renewable energy-based DERs, such as wind power plants, is mainly dependent on (variable) environmental conditions and is therefore uncontrollable. These sources cannot provide reliable and quality power to the network under all operating conditions. Therefore, the presence of diesel generators alongside renewable energy sources can increase the reliability of the power distribution network.[5]

With the development of microgrids, the use of voltage source converters as the interface between DER sources and the power system is increasing. These devices inject the power generated in DER sources under a certain voltage-frequency into the microgrid and provide the conditions for controlling the power components (active and reactive). In wind power plants based on double-fed induction generators, the use of VSC converters on the rotor side and the grid side allows for independent control of the voltage-frequency components in the machine.

It should be noted that the widespread penetration of voltage source converters in microgrids can lead to a reduction in system inertia and damping and take the grid out of synchronous mode. In such conditions, it is possible that with the entry of any disturbance into the microgrid, the system's main state variables may fluctuate and the dynamic stability and safe operation of the grid may be weakened. In addition, a microgrid consisting of multiple VSCs includes a wider range of dynamic processes with different time scales compared to traditional power grids, and therefore its oscillatory modes are located in different frequency bands (from DC to several hundred Hz). Accordingly, the dynamic characteristics of microgrids are distinct from those of classical power systems, and it is necessary to design complementary and stabilizing controllers for these systems by providing an appropriate dynamic model. Wind power plants have different performance characteristics from fossil power plants, and therefore power system operators need to apply new requirements to connect these power plants to power systems. Most wind power plants use induction generators in their structure. These generators absorb reactive power and therefore can affect the voltage at the point of connection to the grid. On the other hand, the amount of wind will vary at different times of the day and night, and therefore the active power injected into the grid by the wind power plant (as well as the frequency of the generated power) can also vary [5-8]. Therefore, in general, wind power generation sources have an impact on the voltage and frequency components of the grid, and their proper control can be effective in improving the stability margin of these components.

The expansion of the power system size and the significant penetration of wind turbines in the network have also increased its complexity and caused disturbances in one area to affect the entire power system. Large-scale outages in Europe and the United States show that despite the progress in the design of hybrid power systems, these systems still operate near their stability limits, and therefore it seems necessary to improve the performance and conduct dynamic studies of these systems.[6]

To improve the performance of the power system including conventional power plants and wind power sources (hybrid system), the use of complementary control loops in voltage source converters, which are the interface between new power plants and the power grid, has been proposed. In addition to controlling the power flow in the system regardless of system conditions, these systems also improve the dynamic stability of the system (damping power fluctuations).

In fact, VSCs in a microgrid can act as a barrier against successive disturbances in the system and prevent the creation of voltage-frequency instability in the microgrid. In other words, the use of VSC technology and their complementary control loops also increases the reliability of the power system. It should be noted that if voltage source converters (VSC) are used in AC microgrids, independent control of active and reactive powers is also provided.

In this research, an integrated control strategy is proposed for VSCs of an AC microgrid including a wind turbine equipped with a DFIG and also a diesel generator. The main goal of this strategy is to strengthen the stability margin of the microgrid under different operating conditions by using the design of complementary damping controllers in the most effective microgrid VSC.

.3RESEARCH OBJECTIVES

In this thesis, an integrated control strategy is proposed for VSCs of an AC microgrid including a wind turbine equipped with a DFIG and also a diesel generator. The main objective of this strategy is to enhance the stability margin of the microgrid under different operating conditions by designing supplementary damping controllers in the most effective VSC of the microgrid. The most effective VSC is identified to apply supplementary control signals based on the concept of controllability of electromechanical modes through the control inputs of the converters and over a wide range of operating points of the microgrid. Once the appropriate input is determined, the supplementary stabilizing controller that is responsible for enhancing the damping coefficient of the oscillatory modes of the microgrid will be designed. This controller is a neural-fuzzy controller that can produce optimal control signals to enhance the stability margin and improve the voltage profile under different operating conditions of the system.

.4RESEARCH QUESTIONS

Main Question:

 How can the power exchange in a microgrid including induction and asynchronous generators be improved by using supplementary controllers in VSCs?

Sub-questions:

.1Is it possible to dynamically model a microgrid system equipped with synchronous and asynchronous generators?

.2Is it possible to model VSCs in a way that describes the dynamic behavior of these devices?

.3Is it possible to design complementary controllers that are capable of stabilizing and improving the voltage profile in the microgrid?

.4Is it possible to use the concepts of neural and fuzzy networks to design adaptive controllers in VSCs?

.5DEFINITION OF THEORETICAL FOUNDATIONS

Renewable energy sources:

Fossil fuels such as coal and oil are formed from the remains of plants and animals that were buried under the seas in ancient times and are naturally found in mines in solid, liquid, gas or a combination of them [10-15]. The issue of air pollution, greenhouse gas emissions and global warming is one of the most important issues of today's societies, which, given the problems it creates, requires a huge and almost immediate change in the world's energy infrastructure to 100% use of clean and renewable energies. For example, every year 4-7 million people die prematurely and hundreds of millions of others become ill due to air pollution, which can be greatly reduced by using clean and renewable sources.[19-16]

Microgrid Concept:

A microgrid is a low-voltage distribution network that includes low-power distributed generation sources, power converters, energy storage systems, loads, and protection devices. It has the ability to operate in two modes: connected to the grid and independent of the island network. In the grid-connected mode, the main grid is responsible for matching production and consumption, and in the off-grid mode, the energy sources within the microgrid are responsible for off-grid.

In the normal mode, the microgrid is connected to the national grid through a point of common connection (PCC) and there is a possibility of exchanging power with the upstream grid. However, in the case of a blackout in the national grid or low grid power quality, the microgrid is disconnected from the main grid and operates as an island. In this case, the distributed generation sources (DER) must provide the necessary power to continue operating the microgrid, and the voltage and frequency of the microgrid are continuously monitored through the control of the existing inverters.[28]

Distributed generation sources:

It was said that due to the expansion of various industries and the increase in energy consumption, as well as due to the limitation of energy resources, fossil fuels and the increase in environmental problems such as geothermal, the need for a suitable alternative source is felt [1]. On the other hand, due to the advancement of technology and the reduction in the cost of equipment in recent years, the use of renewable energy sources (RES) is increasing day by day and it is predicted that in the coming years, the majority of the world's consumption will be covered by renewable energy sources. Also, in networks with a traditional structure that consists of three parts, generation, transmission and distribution. Power is generated on a large scale and in a centralized manner, often far from residential areas, and its transmission to the place of consumption requires high costs and also involves many losses. Loss of quality, power, voltage instability, short circuits in the transmission path and the need to change voltage levels and use transformers are other consequences of this that cannot be ignored.[36]

AC/DC coupling converters: In systems such as uninterruptible power supplies, FACT devices, motor speed control drives, reactive power compensation systems, etc., where AC sinusoidal waveforms are used, the use of converters in power electronic systems to produce an AC sinusoidal waveform with a desired frequency and amplitude from a DC input voltage source becomes doubly important. Converters play an important role in most distributed generation sources. Since power grids, AC microgrids, and most single-phase and three-phase loads operate with AC currents, and on the other hand, the current generated by DC microgrids is direct current, the possibility of exchanging power between two microgrids or supplying the required power to the load in hybrid microgrids is realized through coupling converters. In AC/DC coupling inverters, parameters such as factor, power THD, current and voltage, power quality, protection against system islanding, etc. are important. To produce a desired AC sinusoidal waveform at the output, three parameters, frequency, amplitude, and phase, must be controllable.

Different Topologies of DERs:

DERs are small-scale energy generation and storage systems distributed across a local area such as homes, businesses or industrial facilities. These sources can include renewable energy sources such as solar panels and wind turbines and energy storage systems such as batteries and backup generators. They have different topologies and can operate in islanded, grid-connected and microgrid modes.

.6ELECTRICAL SYSTEM DESCRIPTION AND VSC MODEL

The model of a VSC is schematically shown in Figure 1-1, where the considered network is of three-wire three-phase type and the VSC exchanges two levels of power between the AC side. The converter consists of three branches with two insulated gate bipolar transistors (IGBT). The midpoint of each branch is connected to a different phase of the network using inductances to allow smooth connection to the network of the device. Anti-parallel diodes are connected to the IGBTs to prevent very high voltage peaks in the transistors generated by the inductances when responding to high current derivatives.

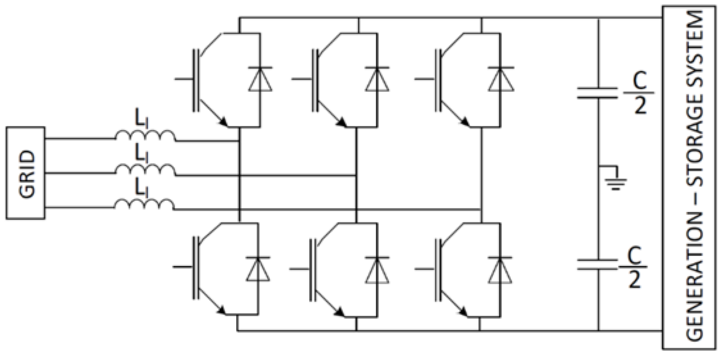

Figure 1 - The system under analysis includes a VSC converter and a three-phase grid. The power generation or storage source is connected to the DC side, which can be either a current source connected to a shunt capacitor or a DC voltage source (used for simulation with storage power generation), while the AC side is modeled as a Thevenin equivalent city grid.

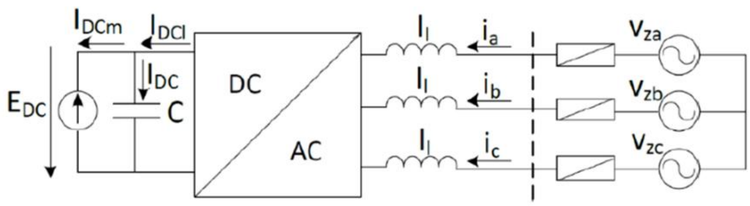

Figure 2 - VSC with DC side modeled as current

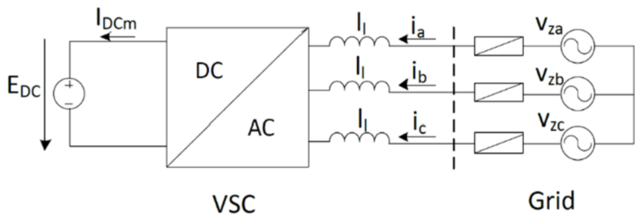

Figure 3 - VSC with DC side modeled as a voltage source

Again, for simplicity, although the VSC is based on discrete IGBT switching modes, for control design purposes it is more convenient to derive a simpler equivalent model.

Eksplorium *p*-ISSN 0854-1418
Volume 45 No. 2, November 2024: 132–144 *e*-ISSN 2503-426X

.1.6VSC Model

The VSC allows to control two electrical variables in a simultaneous frame, allowing separate control of active and reactive power.

The VSC allows to control two electrical variables in a simultaneous frame, allowing separate control of active and reactive power. The reactive power reference is obtained from a higher control level (grid operator or simply the user) or is set to a certain value, while the active power reference depends on the nature of the source connected on the DC side:

•For renewable energy systems, it is set to regulate the DC bus voltage and ensure power balance, ensuring that the power injected into the grid must be the same as the power generated.

•For storage systems, it is set to charge the battery or inject power into the grid, depending on the EMS MG function or the system in which the storage system is connected.

Renewable energy generation is considered first, since it is a more complex case in which a DC voltage controller is required. For storage systems, it is sufficient to eliminate the DC voltage controller and directly generate the active power reference.

The model is developed using the MATLAB/SIMULINK software package and is made up of several blocks that can be divided into two main subsystems:

•The power subsystem, which is directly connected to the DC generation component and to the AC grid. It receives input from the control subsystem to properly interface the DC source, whose voltage is controlled and stabilized, with the grid.

•The control subsystem (in turn formed by several sub-blocks) in which reference signals are sent from a higher-level control system and the grid inputs are taken from it. Once it calculates the correct values for the proper operation of the entire power system, these signals are sent to the converter to be performed.

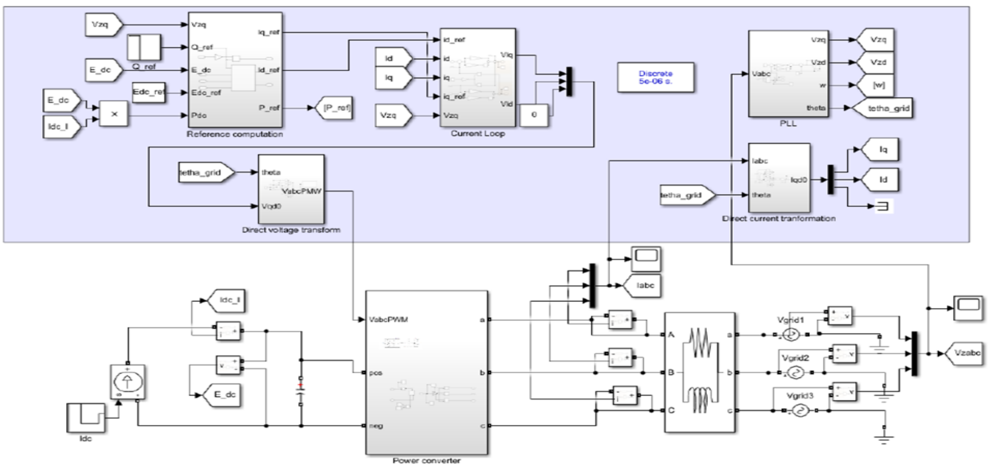

Figure 4- Average model for VSC converter, created with MATLAB/Simulink. On the left is the DC source as a programmable current source, in the center is the power subsystem, on the right is the three-phase AC network modeled as three controlled voltage sources.

.7STUDY NETWORK

The hybrid microgrid system configuration considered in this study is presented in Figure 5- which consists of three main components. In this configuration, the wind turbine, diesel generator and load are considered.

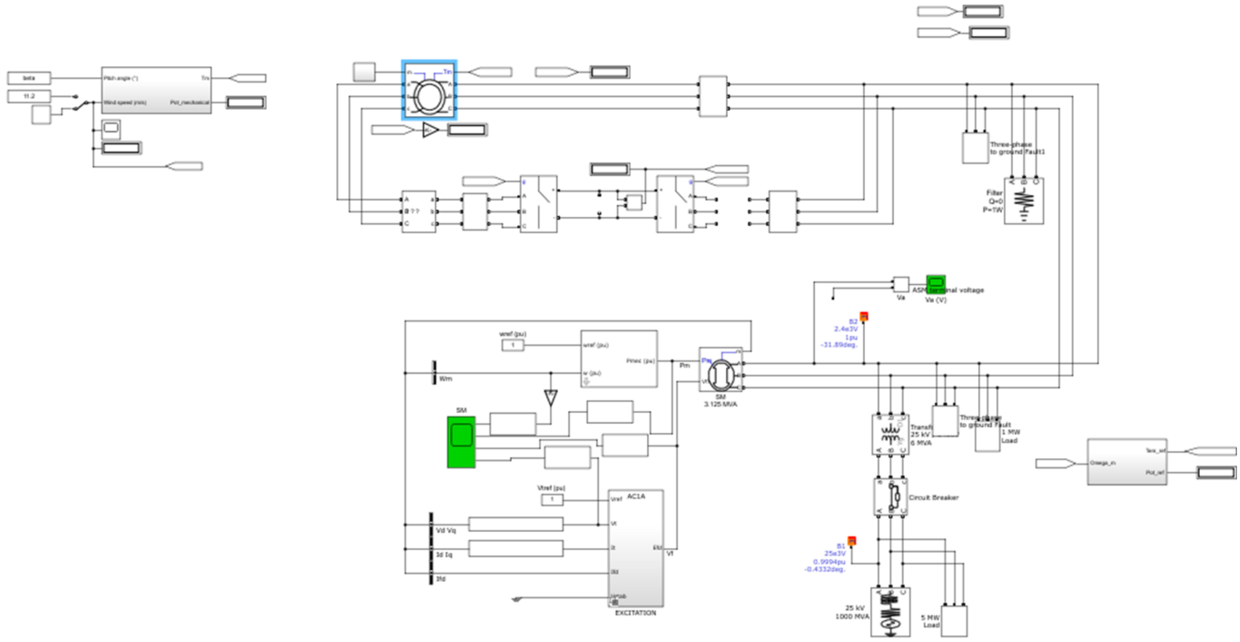

Figure 5- Structure of the hybrid microgrid studied in the research

Design of the power source controller:

The control considered in this research is of the neuro-fuzzy type. It was shown in several articles that the fuzzy logic-based controller for the intermediate converters has achieved very good results. Therefore, in this thesis, in order to achieve better results in key system parameters such as power, frequency and voltage, a neuro-fuzzy controller is presented using two voltage and current inputs as well as a neuro-fuzzy weight optimization algorithm to help reduce distortions and disturbances in the event of errors in the network and in dynamic mode.

Fuzzy controller:

The general structure of fuzzy controllers is shown in Figure 6-. This controller has two inputs: non-fuzzy output error (ex) and output error changes (Aex). For the system, two inputs and one output are considered, where the inputs ex=Vout-Vref (non-phase output error) and 1-Aek-ek-ek (non-phase error changes) and the output dD (duty cycle change) are selected. The error signal changes are defined as follows.

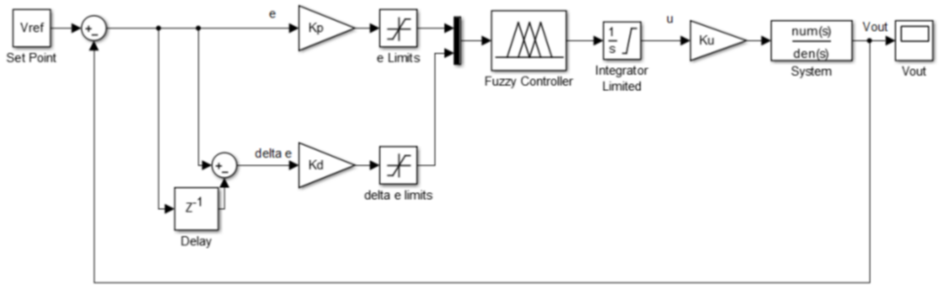

Figure 6 - General block diagram of a conventional fuzzy controller.

Figure 7 also shows the rules set for the input and output signals of the fuzzy controller.

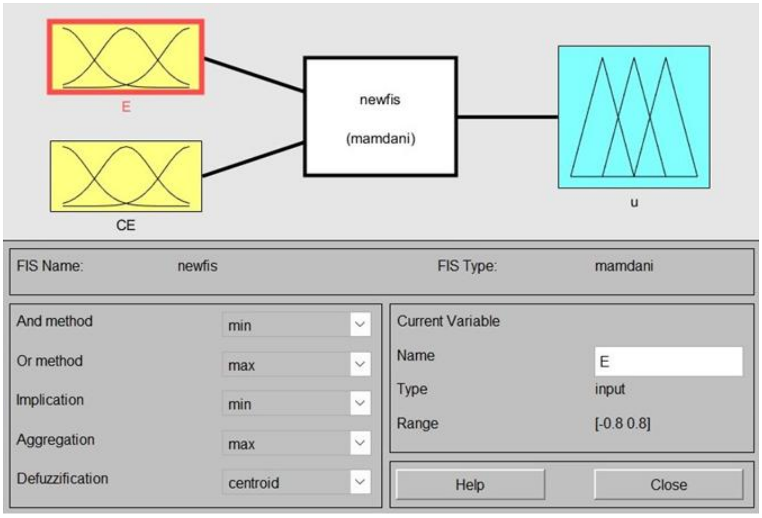

Figure 7- Fuzzy controller rules

.1.7Simulation results

In this section, the simulation results without a fault in the network are first presented, and then the results of a fault in the network are examined to examine the network capability in fault conditions. Also, the controller's performance in fault and islanding conditions is also examined.

First, the simulation results in the no-fault state are presented so that a comparison can be made between the results in the fault state and the corresponding controller. Figure 8- and Figure 9- show the current waveform and three-phase voltages of the microgrid. It is noted that the nominal voltage of the microgrid, which is the nominal voltage of the diesel generator and wind turbine, is 220 volts, which is the nominal voltage of each source presented in the previous section. Here, it is also observed that after the transient period, the voltage and current waveforms initially reach their steady state.

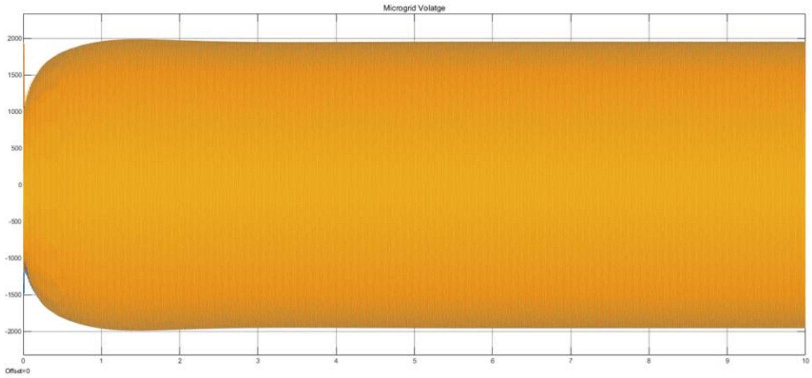

Figure 8 - Three-phase microgrid voltages

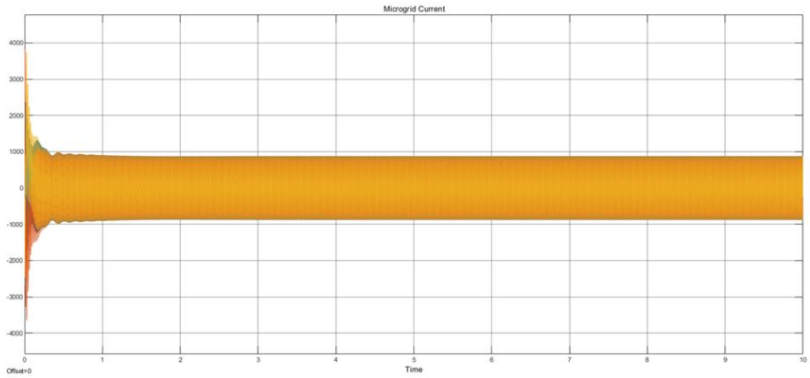

Figure 9 - Three-phase microgrid currents

Network results when a fault occurs:

Similar to the process followed in the network results without a fault, in this section the results are exactly repeated to measure the changes that occurred in various parameters under fault conditions.

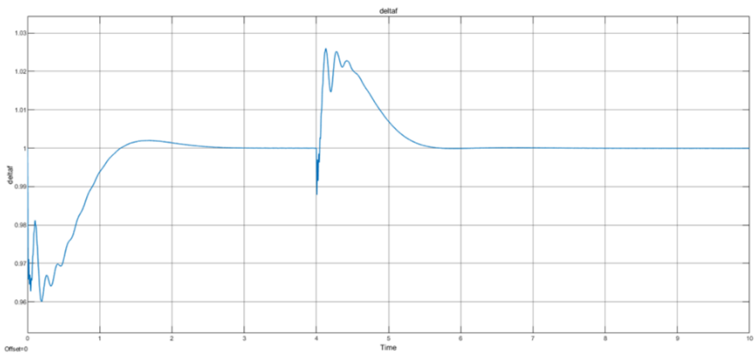

Figure 10- Network frequency deviation during fault

Figure 10 and Figure 11 show the network frequency deviation during fault and the mechanical power changes of the diesel generator during fault, respectively. As can be seen, the frequency increased by 0.025 per unit during fault and reached its steady state after 1 second. Figure 11 shows the generator power changes. A notable point in the results is that the duration of the changes is less than 1 second, which has a shorter settling time than PID and FOPID controllers.

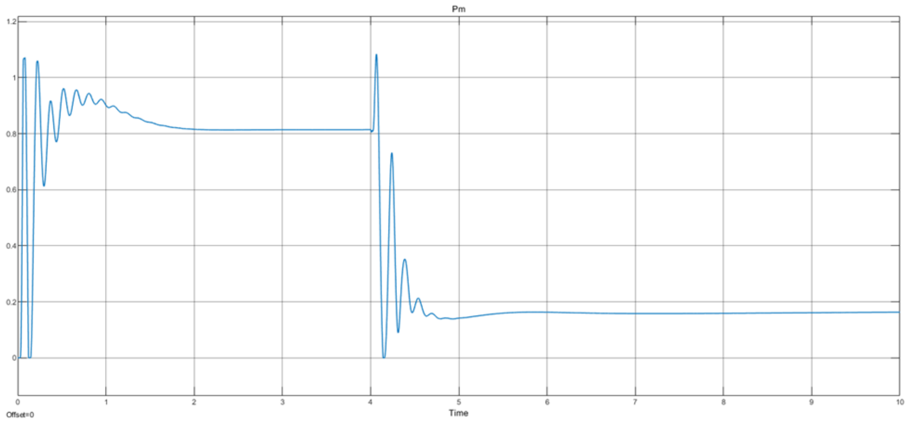

Figure 11 - Changes in mechanical power of diesel generator during fault

8- CONCLUSION

In general, the results obtained in this study are:

1- The results showed that using a neural-fuzzy network can reduce the disturbances caused by faults in the microgrid.

2- The results of using a neural-fuzzy network-based controller with current and voltage control inputs can be used in VSCs on the grid side and stator side in a wind turbine with an asynchronous generator.

3- In this thesis, the connection of two wind turbines and a diesel generator, which represents the connection of synchronous and asynchronous generators, was investigated, and the results showed that the presence of multiple sources can be easily used in a network.

4- The results showed that in the event of a fault in the network, the frequency ripple is controlled within a limit of 0.005 per unit using a neural-fuzzy controller.

5- The time taken to reach the initial state of the network after the fault occurs is 1.5 seconds, which in previous studies was more than 5 seconds, which is a much shorter time compared to them.

6- The results showed that the main network voltage without ripple and change in voltage completely transfers 1 per unit of power to the load.

9. INNOVATION

The innovation of the present study can be considered in presenting a new control scheme that is obtained by adding current control loops to the classic VSC control circuits that use the voltage parameter in the control loop, which has not been addressed in any research so far. Also, in this thesis, an optimized neuro-fuzzy controller was used to minimize the dynamic response due to disturbances. It should be noted that in a fuzzy neural network, the weights of the neural network are assigned randomly, which reduces the accuracy of the neural-fuzzy network. Therefore, in this thesis, the Wall metaheuristic algorithm was also used to optimize the weights of the neural network.

10. SUGGESTIONS

In this section, based on the studies conducted, some suggestions are presented to be examined in future research and for researchers and enthusiasts to take ideas from them and use them in their work.

1- It is suggested that in future studies, the complete network including renewable sources, batteries, and also electric vehicles be considered in the modeling, and the VSC converters in them and finally their connection in the shell should also be examined.

2- It is suggested that in future studies, FOPID controllers and their optimization using metaheuristic algorithms should be used in the controller.

3- It is suggested that in future studies, newer controllers should be used to reduce voltage fluctuations and frequency ripple to increase network resilience.

4- It is suggested that in future studies, studies should also be conducted on IEEE standard networks and a constant power voltage source connected to an infinite bus should be connected to the real network to examine the strength of the method in the real network.

11. REFERENCES

[1] Haider, Z.M.; Mehmood, K.K.; Rafique, M.K.; Khan, S.U.; Lee, S.-J.; Kim, C.-H. Water-filling algorithm-based approach for management of responsive residential loads. J. Mod. Power Syst. Clean Energy 2018, 6, 118–131.

[2] Khan, S.U.; Mehmood, K.K.; Haider, Z.M.; Rafique, M.K.; Khan, M.O.; Kim, C.-H. Coordination of multiple electric vehicle aggregators for peak shaving and valley filling in distribution feeders. Energies 2021, 14, 352.

[3] Rafique, M.K.; Khan, S.U.; Zaman, M.S.U.; Mehmood, K.K.; Haider, Z.M.; Bukhari, S.B.A.; Kim, C.-H. An intelligent hybrid energy management system for a smart house considering bidirectional power flow and various EV charging techniques. Appl. Sci. 2019, 9, 1658.

[4] Rafique, M.K.; Haider, Z.M.; Mehmood, K.K.; Zaman, M.S.U.; Irfan, M.; Khan, S.U.; Kim, C.-H. Optimal scheduling of hybrid energy resources for a smart home. Energies 2018, 11, 3201.

[5] G.P. Prajapat, N. Senroy, I.N. Kar, "Wind turbine structural modeling consideration for dynamic studies of DFIG based system", IEEE Trans. on Sustainable Energy, vol. 8, no. 4, pp. 1463-1472, Oct. 2017 (doi: 10.1109/TSTE.2017.2690682).

[6] M.S. Alam, M.A.Y Abido, "Fault ride through capability enhancement of a large-scale PMSG wind system with bridge type fault current limiters", Advances in Electrical and Computer Engineering, vol. 18, no. 1, pp. 43-50, Feb. 2018 (doi:10.4316/AECE.2018.01006).

[7] Beza, Mebtu, and Massimo Bongiorno. "Identification of resonance interactions in offshore-wind farms connected to the main grid by MMC-based HVDC system." International Journal of Electrical Power & Energy Systems 111 (2019): 101-113.

[8] Mohamed, Y.A.R.I.; Radwan, A.A. Hierarchical Control System for Robust Microgrid Operation and Seamless Mode Transfer in Active Distribution Systems. IEEE Trans. Smart Grid 2011, 2, 352–362.

[9] Wang, X.; Li, Y.W.; Blaabjerg, F.; Loh, P.C. Virtual-Impedance-Based Control for Voltage-Source and Current-Source Converters. IEEE Trans. Power Electron. 2015, 30, 7019–7037.

[10] Doolla, S.; Bhatti, T. Load Frequency Control of an Isolated Small-Hydro Power Plant with Reduced Dump Load. IEEE Trans. Power Syst. 2006, 21, 1912–1919.

[11] Gonzales-Zurita, Ó.; Clairand, J.M.; Peñalvo-López, E.; Escrivá-Escrivá, G. Review on Multi-Objective Control Strategies for Distributed Generation on Inverter-Based Microgrids. Energies 2020, 13, 3483.

[12] Gupta, A.; Doolla, S.; Chatterjee, K. Hybrid AC–DC Microgrid: Systematic Evaluation of Control Strategies. IEEE Trans. Smart Grid 2018, 9, 3830–3843.

[13] Golsorkhi, M.S.; Lu, D.D.C. A Control Method for Inverter-Based Islanded Microgrids Based on V-I Droop Characteristics. IEEE Trans. Power Deliv. 2015, 30, 1196–1204.