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Transient Enhancement of Smart Grid Using SMES Controlled by PID and Fuzzy Logic Control

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Abstract: A Smart Grid is an electrical system that is comprised of energy sources, controls, computers and equipment integrated to operate as a unit in the form of an electrical grid to respond to changing power demands. Renewable energy technologies such as a wind turbine are part of this unit. The output power of wind generators experiences dramatic daily fluctuations that are caused by changes in weather patterns. This may adversely affect the power quality and system. To mitigate the effects of these variations, energy storage devices (ESDs) such as superconducting magnetic energy storage system (SMES) can be incorporated into the power system to enhance transient performance and inject or draw electricity to the grid as required. The important role of SMES in the system is to control the system by improving transient stability, which is achieved by use of control technologies. VSC-Based SMES has been used. In this paper, a Proportional-Integral-Derivative (PID) controller and Fuzzy Logic control (FLC) are compared and contrasted. The goal in this paper is to determine which of the two control technologies provides a superior performance while also taking the computational complexity of the simulation into account. Two scenarios in the results have been performed in MATLAB/Simulink 2016b software and the simulation results have validated that FLC is more efficient compared to PID. However, FLC takes approximately 70% more control time.

Keywords: Fuzzy Logic Controller (FLC), One Line to Ground Fault (L-G), Proportional-Integral-Derivative (PID), Energy Storage Devices (ESDs), Superconducting Magnetic Energy Storage (SMES)

1. Introduction

The climate change menace, coupled with the knowledge that fossil fuel reserves may be depleted over a period of time, has resulted in the rapid inclusion of renewable energy technologies. These technologies are integrated into the power utility grid to reduce our dependence on fossil fuels and non- renewable energies as a whole. However, the most prominent renewable energy sources, namely solar and wind, are weather-dependent, intermittent, and influenced by natural conditions which makes their power output highly unstable due to voltage fluctuations [1, 2].

In addition, an increase in electrical demand worldwide has made power systems more complex, which can compromise power system reliability and quality. As a result, electricity from these technologies needs to be stored first, then injected into the grid according to power system requirements and characteristics such as voltage, frequency, harmonic content, power peaks, flicker, etc. This will improve competitiveness and enhance transient behavior of the power system.

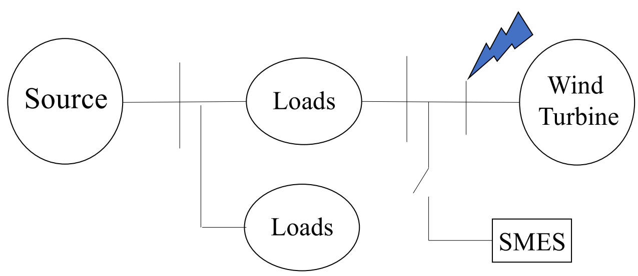

Figure 1. *Block diagram for the presented system.*

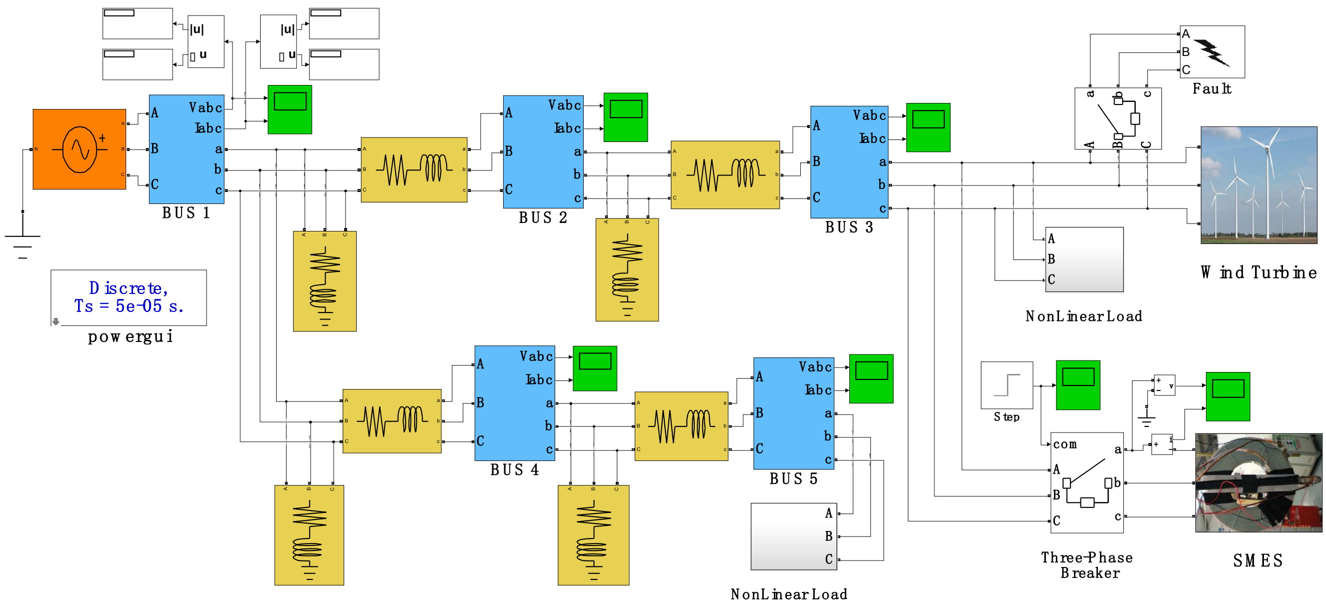

Figure 2. *IEEE 5 bus smart grid including wind turbine and SMES.*

Energy Storage Devices (ESDs) have a high potential of improving the transient stability of power systems during rapid changes in energy demands [3]. Several traditional and modern technologies can be used to store energy and provide stability [1, 3–5]. Most storage devices suffer from limitation in life time, limitation in charging and discharging times, sizing requirements, and speed of processing due to impure electric conversion [3, 5–7]. However, Superconducting Magnetic Energy storage (SMES) is able to provide a fast response [5–9]. Moreover, SMES is capable of unlimited charging and discharging of energy. Also, SMES is capable of high storage efficiency [5–7] which exceeds 97% [3].

The concept of SMES began in the early 1970's. The central underpinning was that the amount of energy generated by nuclear power would be more than enough to power the world, and that our reliance on fossil fuels could be reduced to only being used during moments of peak demand. Power utilities would be required to smooth the daily differences between peaks and valleys of load consumption throughout the day. Additionally, storage could be needed to store sufficient energy to eliminate or minimize the use of the fossils fuels in electricity generation. Early designs of SMES concentrated on superconducting coils that could store more than 5 GWh, since the focus was purely on large-scale load leveling [9, 10].

Based on the topographic configuration of the SMES, there are three types of power conditioning systems (PCSs) that are responsible for power transfer between the AC system (AC bus) and the superconducting coil. These classes are the voltage source converter (VSC)-based, the current source converter (CSC)-based, and the thyristor-based SMES [3, 5]. Thyristor-based SMES is easy to control, however, it is only applied in systems that require control of the active power and has minimal effect in controlling reactive power. VSC- and CSC-based SMES are employed in systems that require the control of both reactive and active power independently [3, 5, 11]. Moreover, thyristor- and CSC-based SMES have only an AC/DC converter in their models while VSC-based SMES has both an AC/DC and a DC/DC chopper. However, VSC-Based SMES is considered complicated to control when compared to others [5].

In a paper by Y. Q. Xing, J. X. Jin, Y. L. Wang, B. X. Du and S. C. Wang, CSC-based SMES was used in the model and indicated that CSC-based SMES is easy to control, simple to design and less expensive [11]. The system proposed by D. Wu, K. T. Chau, C. Liu, S. Gao and F. Li included thyristor-based SMES due to the flexibility to control SMES for charging and discharging modes [12]. On the other hand, authors preferred to use VSC-based SMES which can control active and reactive power independently and has the ability to convert either a DC/DC or an AC/DC [3, 4].

There are three main types of wind turbine generators that have been addressed and detailed, which are discussed as follows. The first is a variable speed wind turbine system with a gearbox and a permanent magnet synchronous generator (PMSG). Second, a variable speed wind turbine system with a gearbox and a doubly-fed induction generator (DFIG). Finally, a fixed-speed wind turbine system that employs a gearbox and a standard squirrel cage induction generator (SCIG), which was excluded for the time being [2].

Since controlling the signal is considered an essential aspect to the application of SMES devices, there are various control technologies employed to achieve intended objectives. Some of the commonly used control algorithms include proportional integral (PI), proportional integral derivative (PID), fuzzy logic controller (FLC), static var compensator (SVC), static synchronous compensator (STATCOM), and model predictive control (MPC), among numerous other algorithms. The PI and PID control algorithms are the most widely used in the industry at present. This is because PID controllers are less expensive and are easy to tune. However, they mainly solve mono-variable control problems and are inefficient in tackling multivariable constraints which form integral parts of real physical systems. Moreover, PI and PID controllers have to be redesigned when a new component is added to the power system [3, 13, 14]. MPC is an effective practical technique to handle such systems. It is a control technique that is based on numerical optimization where future control inputs and future plant outputs at each interval can be predicted [3]. On the other hand, FLC is a powerful problem-solving technique with numerous applications in information processing and embedded control. There are some advantages for FLC such as its robustness, an absence of need of a transfer function for the systems, and convenience for nonlinear systems [14].

Also, M. Hasan Ali, T. Murata and J. Tamura studied FLC based SMES to improve transient stability of an electric system and compared it with the conventional proportional integral (PI) controlled SMES [14]. The authors illustrated FLC's effectiveness in improving stability by considering unbalanced and balanced faults in the system. In addition, the study compared the ability of fuzzy logic-controlled SMES and fuzzy logic-controlled braking resistor (BR) to control transient stability. The outcome of the study shows that both FLC and PI controlled SMES are effective enhancers of transient stability for both balanced and unbalanced faults, though FLC has better performance. In the other comparison, FLC controlled SMES performed its operations faster than FLC controlled BR.

Two ESDs are addressed and listed as (SMES) and battery energy storage system (BESS). The authors proposed an MPC controller to control both ESDs and compared the results with a PID controller to control also both ESDs. By focusing only on the SMES device results in both controllers, they resulted same active and reactive output power of wind turbine as well as same voltage sag. Additionally, the PID controller was able to damp the voltage swell in one of the phases better than the MPC controller after the switch turned on. Despite authors introduced the MPC controller, the PID is recorded better results by controlling SMES. This has made the authors conclude by saying that the PID controller is fair to use instead of MPC to control SMES [3]. The study is well done and proposed good quality results which have been extended here by proposing the fuzzy logic control algorithm to control SMES as well.

As is known, several fault types accrue in power systems including lightning, heavy rains, heavy winds, or damages to the transmission lines. These phenomena cause transients to the grid. This paper presents an analysis of the system's dynamic performance under unbalanced faults such as a one line ground to fault.

This paper presents a system model as shown simplistically in Figure 1. A wind turbine and a Superconducting Magnetic Energy Storage System (SMES) are used for this study. For more clarification, Figure 2 shows a five-bus smart grid implemented in MATLAB. VSC-Based SMES has been chosen. The bus which connects the wind turbine to the rest of the grid is called the Point of Common Coupling (PCC). So, the SMES is connected to the same bus as the wind turbine. By extending the work in [3], this paper compares the SMES controlled by PID against that controlled by a fuzzy logic control.

This paper is organized as follows: Section 2 elaborates the system SMES and control diagram as well as covers FLC rules. Section 3 illustrates different types of energy storage devices including SMES. Section 4 provides simulation results of two different scenarios. Finally, the conclusion will be shown in section 5.

2. System Configuration

2.1. SMES System and Control Model

Figure 3(a) shows that SMES block parameters which include VSC, controller, Pulse With Modulation (PWM), capacitor, DC-DC chopper, as well as a high-temperature superconducting (HTS) coil. Also, Figure 3(b) shows the SMES equivalent circuit parameters. The converter (VSC) is used to control both the reactive as well as the active power independently and simultaneously. The DC-DC chopper, on the other hand, controls the flow of current through the superconducting coil which is determined by G_1 and G_2. Both G_1 and G_2 are power electronic switches which are responsible for charging or discharging the HTS coil according to the following conditions which summarized in Table 1. When G_1 and G_2 are both unit voltage vectors, the SMES stores power to the coil which can be called charging mode. When both G_1 and G_2 are zero, the discharging mode occurs and SMES releases power to the grid. However, there is a third mode, called freewheeling mode, when G_1 and G_2 are not equal to each other. In this case, the current circulates between DC-DC chopper and the coil with no losses. Moreover, the VSC and DC-DC chopper are linked by a DC capacitor [3].

Figure 3(c) elaborates the controlling block which is shown in Figure 3(a). The Park Transform block (abc/dq0) is used in the controlling block to convert AC three phase signal to direct quadrature zero, DC form. The reason of using this is that the DC value is easy to control. Then, the FLC/PID controls the signal. After the signals is controlled, it converts back by using an Inverse Park Transform block in order to obtain the three phase signals. Then, signals connect to the (PWM). There are six pulses generated by a Pulse Width Modulation (PWM) rectifier/inverter that transfer to the control VSC.

A DC current was shown to generate a magnetic field when passed through the coil. The stored energy in Joules and rated power in Watts are shown in (1) and (2) respectively [6, 15, 16]. They can be expressed as:

$$E = \frac{1}{2} L I^2 \quad (1)$$

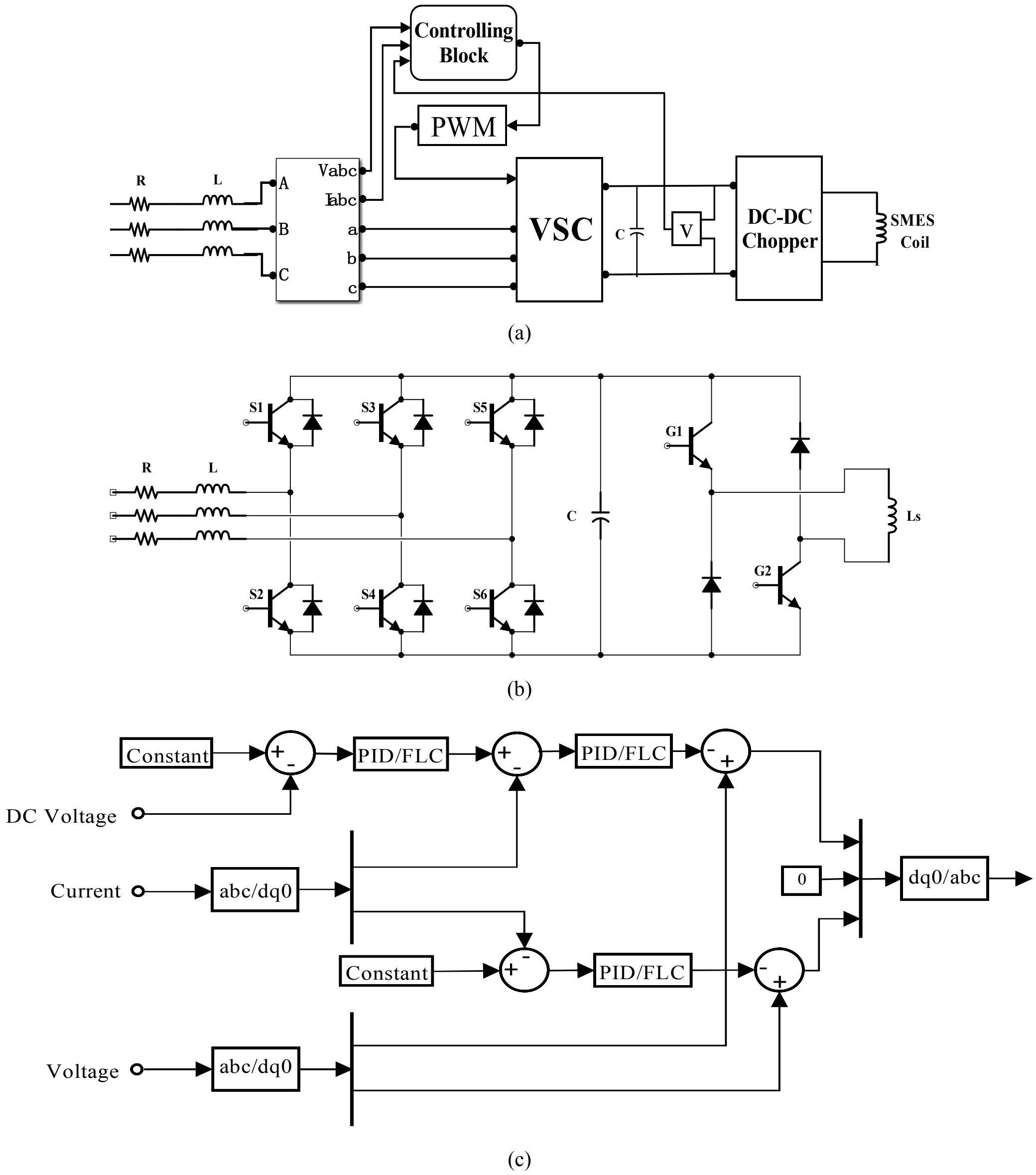

Figure 3. *(a) Typical topology of SMES block including the controller; (b) Main circuit of SMES using VSC; (c) Controlling block.*

$$P = \frac{dE}{dt} = L\,I\frac{dI}{dt} = VI \quad (2)$$

where E is total stored energy in the coil, L is the inductance of the coil, V is the voltage across the coil, and I is the current through the coil. Moreover, the current which passes through the coil during charging mode at any time t is expressed in (3), and the current which passes through the coil during discharging mode at any time t is expressed in (4) [11]:

$$I(t) = I(0)\,exp\left(-\frac{Rt}{L}\right) + \frac{V_{dc}}{R}\left[1 - exp\left(-\frac{Rt}{L}\right)\right] \quad (3)$$

$$I(t) = I(0)\,exp\left[-\frac{(R+R_{load})t}{L}\right] \quad (4)$$

where *I(0)* is the initial current through the coil, V_{dc} is the DC voltage of the converter, R is the resistance of the DC side of the converter, and R_{load} is equivalent load resistance.

Table 1. *Voltage vector of dc–dc chopper.*

G_1	G_2	V_s
0	0	$-V_{dc}$
0	1	0
1	0	0
1	1	V_{dc}

Table 2. *Fuzzy Rules.*

Output α		Deviation Rate Δ		
		N	Z	P
Variable value	N	S	D	D
	Z	A	S	D
	P	A	A	S

2.2. Fuzzy Logic Control (FLC) and Input/Output Membership Functions

The FLC method resembles a human-like ability to make decisions based on an approximate data set and find precise solutions. It is a branch of logic that permits infinite levels of logic (between 0 and 1) to solve a problem containing many imprecise situations and uncertainties. Fuzzy control process is based on a fuzzy logic characterized by "IF - THEN" rules [14].

On the proposed FLC, it has two inputs and one output. The inputs are the membership of variable value and the deviation rate Δ, both called Gaussian membership functions. They have linguistic variables indicated by Positive (P), Zero (Z), and Negative (N). On the other hand, the output is called triangular membership function α represented as Add (A), Stand-by (S), and Decrease (D) [11]. The use of FLC entails following some relevant rules to arrive at the technique. The process begins with a procedure known as fuzzification, which consists of obtaining appropriate membership functions that define the crisp data in order to find the best improvement. To obtain the grade of membership level, this equation of the triangular membership function should be used:

$$\mu_{Ai}(x) = \frac{1}{b}(b - 2|x - a|) \quad (5)$$

where $\mu_{Ai}(x)$ indicates the value of grade of membership, a is the point coordinate, b is the width, and x is the input values [14].

Then, Table 2 is the rules which considered as the heart of the Fuzzy controller. It is consulted to determine the correct output [11]. The process ends with defuzzification where the 'fuzzed' data is converted into crisp data to provide the required information. Using all of this, we begin our investigation.

3. SMES Among Energy Storage Devices

There are many ESDs used worldwide. The most commonly used in the market are classified as follows. First, (BESS) which store electrical energy in chemical form and employ electrochemical reactions to generate a flow of electrons at a constant voltage in multiple cells linked in parallel or series [3, 5]. The technology stores high density energy and its convenient voltage characteristics and size makes it viable for small renewable energy systems. The challenges associated with BESS, however, include limitations in voltage and current, and potential of environmental pollution due to chemical disposal after use and limited life cycle.

The second is the compressed air energy storage (CAES) in which energy is stored in form of potential energy by compressing it in large spaces and used to operate gas turbines. Despite the fact that this technology has a substantial power capacity, the initial investment is high, operation and maintenance costs are also high, and requires special installation locations [3].

The third is the flywheel energy storage (FES) that stores energy in the momentum of a wheel in motion. FES has a considerably long-life cycle as well as high output power density. However, its energy density is low, and has large standby losses [3].

As shown in the previous studies, the energy storage systems discussed above possess a combination of disadvantages ranging from limited life cycle, voltage and current limitations, low energy and impure electric energy conversion which make it slower among others. On the other hand, SMES is being mostly explored to take over storage of electricity and enhance transient stability, dynamic stability, and frequency regulation of power system [5]. SMES stores energy in a magnetic field that is generated via circulation of current through a superconducting coil or inductor [3, 12, 15]. SMES has pure electrical energy conversion, while other energy storage devices involve either electrical-chemical or electrical-mechanical energy conversion, which is much slower [6]. Also, it has a potentially unlimited number of times it can charge and discharge the coil [5–7]. Both active and reactive power can be drawn and injected in a short time using this system [13]. Thus, an SMES was chosen for simulation and testing, which is described below.

4. Simulation Results

As seen the proposed system in Figure 2, an IEEE 5-bus has been chosen in this work and connected with a wind turbine. The SMES is connected in parallel with wind turbines to reduce the fluctuation in the grid. Nonlinear loads, which generate disturbances, are also connected in parallel with wind in order to provide more fluctuations to the PCC bus. So, in this paper, both active and reactive parts of the power of the wind are focused on. Also, two types of wind generators have been taken into consideration which are called DFIG and PMSG. In each circuit, the SMES is controlled by either PID or FLC and a comparison is undertaken. All figures are scaled in pu. The results have been divided into two scenarios in order to test the enhancement of the controllers.

4.1. Connect (SMES-PID/FLC) to the System at 0.3 s

The first scenario is based on the proposed Simulink model shown in Figure 2 where the fault is neglected. The results show an SMES connected to the grid for a certain period of time. The time period before connecting the SMES device to the grid is considered as the "NO SMES" situation. Figures 4 and 5 represent the active and reactive power of DFIG generator respectively. For clarity, two cases indicated as SMES-PID and SMES-FLC are presented in these results. In each case, the energy storage device, SMES, does not function until 0.3s. There is an auto three-phase circuit breaker located between the SMES and the grid which is controlled by pulses to be closed at 0.3 s in order to allow the SMES to start operating. This aids in distinguishing the improvement made by the SMES. The simulation is terminated at 0.5 s. As seen in Figures 4 and 5, FLC exhibits enhancement in smoothing the fluctuations compared with PID using SMES and with NO SMES.

Figures 6 and 7, on the other hand, represent the active and reactive power of PMSG generator respectively. A similar simulation to what was previously mentioned for the wind turbine (DFIG) was also performed on the PMSG. After comparing Figures 6 and 7, transient stability performance has increased. Notably, FLC shows greater improvement, dampens the disturbances, and reaches steady state faster.

4.2. Connect (SMES-PID/FLC) and Add one Line to Ground Fault (L-G)

The second scenario is also based in Figure 2, where the three-phase circuit breaker is removed. The SMES is therefore connected at "bus 3" at all times during the entire simulation. Then the line to ground fault (L-G) is added to the bus containing the SMES and a wind turbine. The fault has occurred at 0.15 s and cleared at 0.25 s. There are three cases of output power of the winds in each figure and are marked as No SMES, SMES-PID and SMES-FLC. Figures 8 and 9 show active and reactive power of the DFIG respectively. Again, the results of output power of this wind show that FLC performs better than the PID and the lack of SMES device. As seen in Figures 8 and 9, FLC exhibits less fluctuation during the whole simulation and specifically during the transient time. Also, after the fault clears, the power using FLC returns back to the steady state faster than the others. Figures 10 and 11, on the other hand, illustrate active and reactive power of PMSG respectively. More transients occurred during transient time where no SMES device was connected. However, the transient amplitude is reduced when the SMES was added to the grid. Controlling SMES by FLC is recorded as the best case. Compared with the three cases, FLC is not only compensating energy through transient time, but also trying to damp the fluctuation and smooth the output power during whole time period.

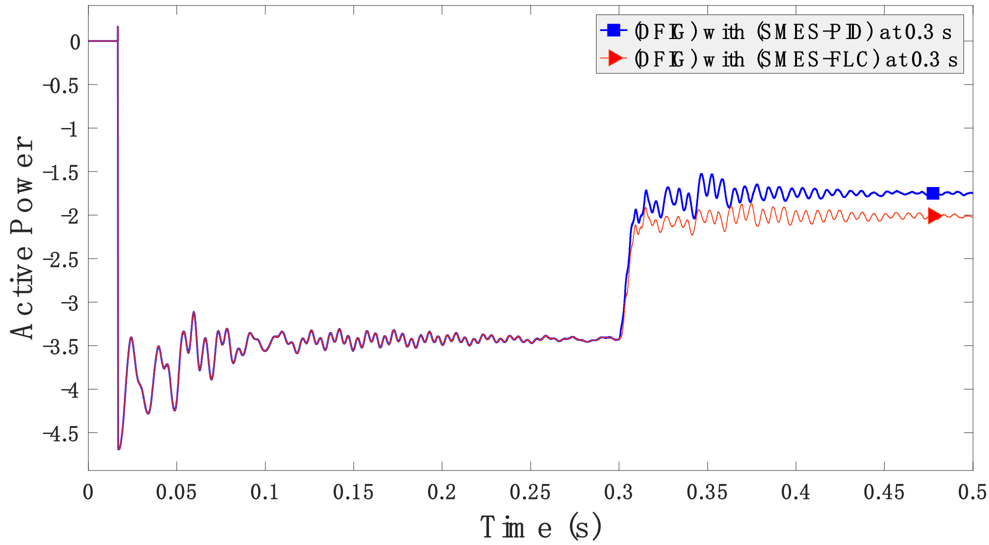

Figure 4. *Active Power of (DFIG wind) with (SMES-PID/FLC) at 0.3 s.*

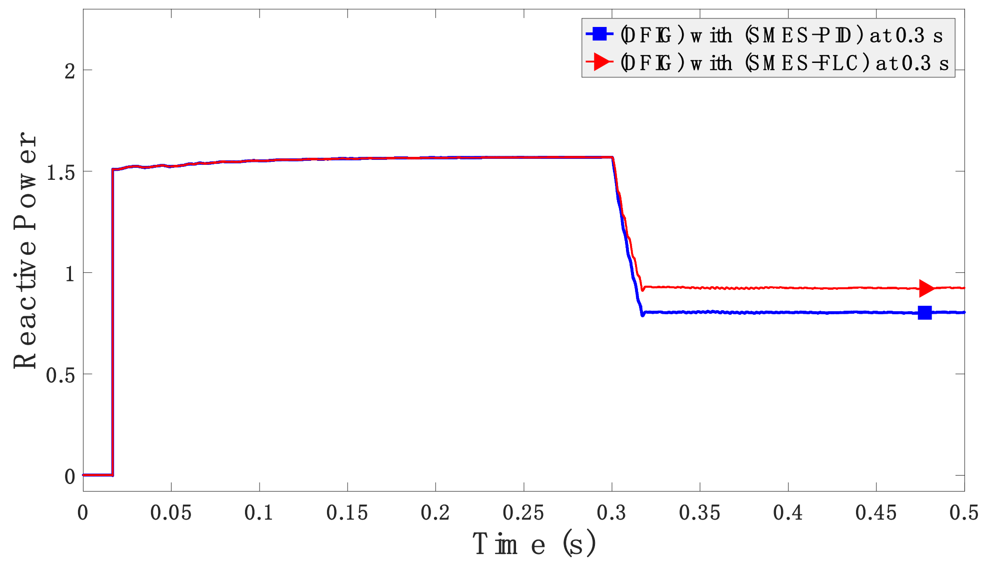

Figure 5. *Reactive Power of (DFIG wind) with (SMES-PID/FLC) at 0.3 s.*

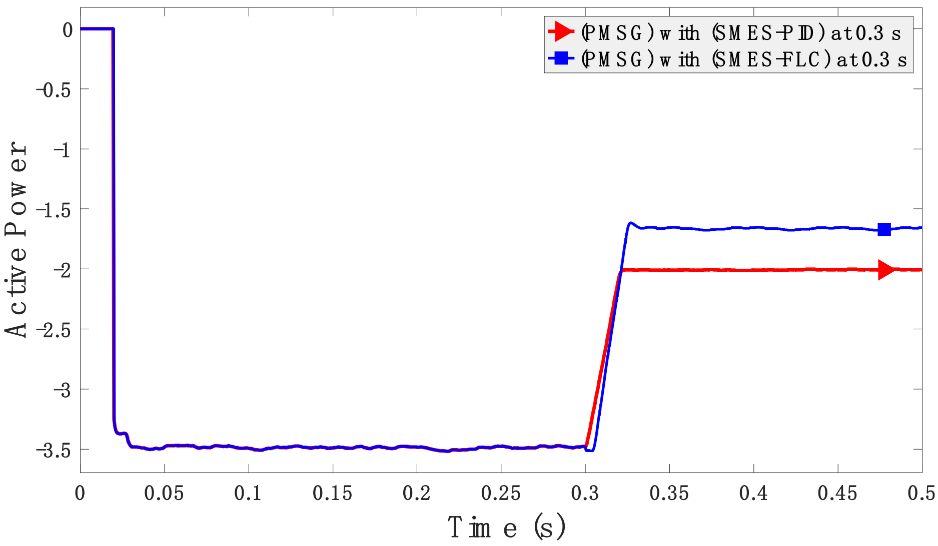

Figure 6. *Active Power of (PMSG wind) with (SMES-PID/FLC) at 0.3 s.*

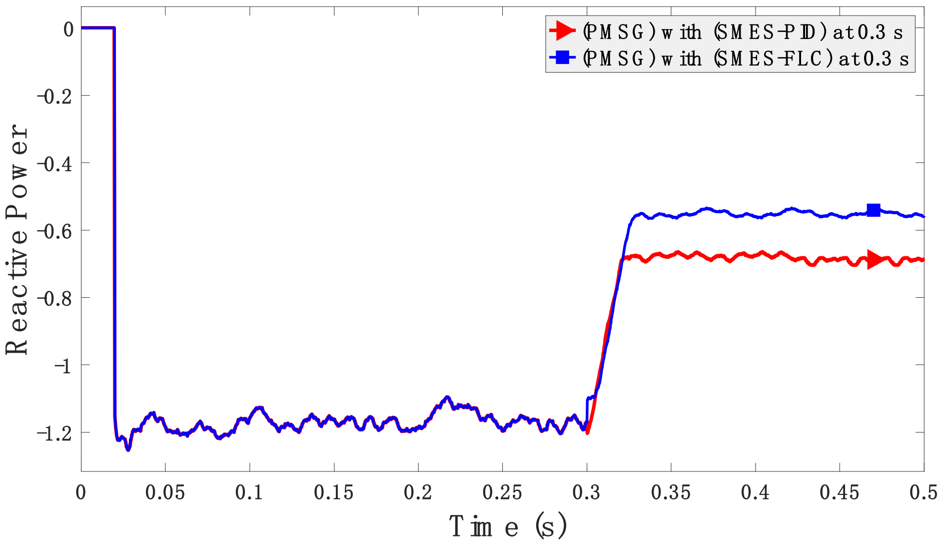

Figure 7. *Reactive Power of (PMSG wind) with (SMES-PID/FLC) at 0.3 s.*

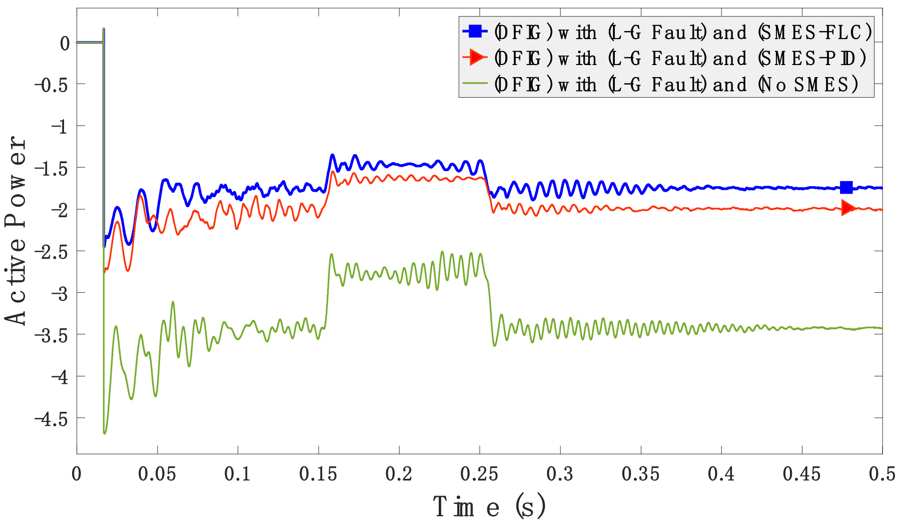

Figure 8. *Active Power of (DFIG wind) with (L - G Fault) and (No SMES, PID, FLC).*

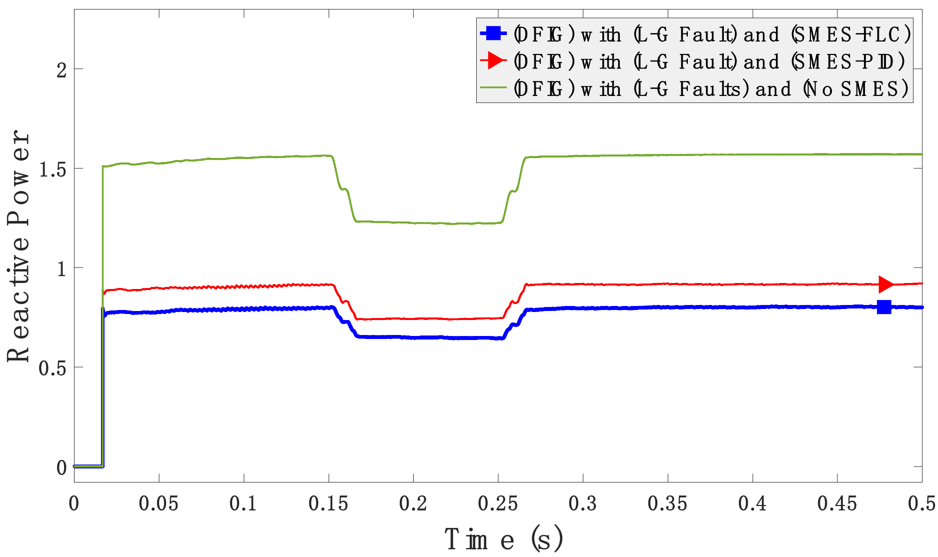

Figure 9. *Reactive Power of (DFIG wind) with (L - G Fault) and (No SMES, PID, FLC).*

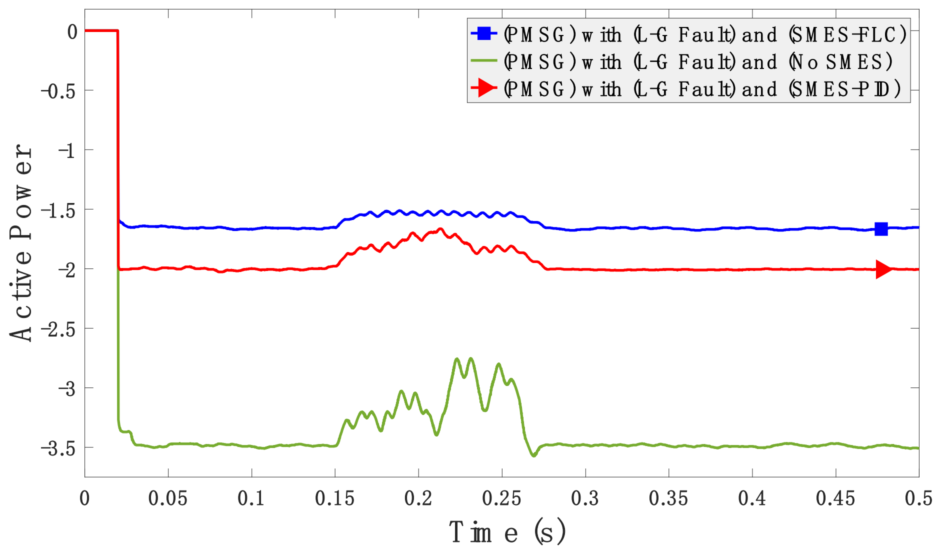

Figure 10. *Active Power of (PMSG wind) with (L - G Fault) and (No SMES, PID, FLC).*

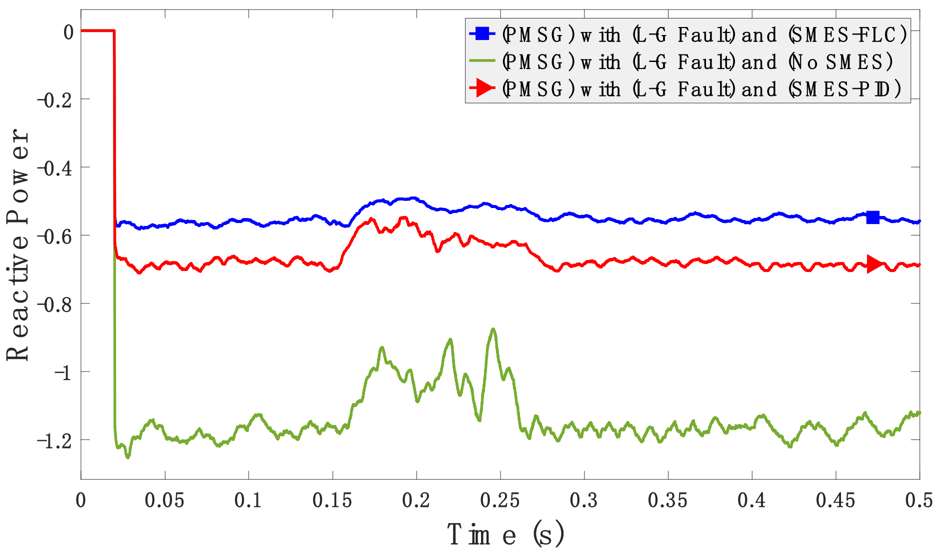

Figure 11. *Reactive Power of (PMSG wind) with (L - G Fault) and (No SMES, PID, FLC).*

5. Conclusion

The incorporation of distributed energy systems such as wind energy systems, photovoltaic, and diesel generators, among others, into the mini grids and utility grid to mitigate greenhouse gas emissions is on the rise. As the demand for energy is skyrocketing, this will play a key role for the future. However, these technologies produce electricity with fluctuating voltages that may cause imbalances in the power network such as the flickering of lamps and limitations in electric devices [15]. Therefore, Power utilities are exploring SMES to maintain and improve the performance in power systems. VSC-Based SMES is used due to its unique advantages such as ability to be AC/AD or DC/DC, and independent control of real and reactive power when passing between the superconducting coil and the grid. It also needs control strategies, among which the most commonly used are PID, PI, FLC, MPC, etc.

This paper compared and discussed two types of controllers, PID and FLC, to control an SMES system. The simulation has been performed using both DFIG and PMSG wind turbine generators. The results from both scenarios show that FLC performed better at minimizing fluctuations in output power than PID at the same smart grid conditions. However, it takes approximately 70% more control time than PID to control the SMES with the same model inputs. FLC was shown to suppress more than PID, as well as and grant less amplitude during fault time. This is especially true in second scenario. Y. A. Sultan, S. S. Kaddah and M. A. Elhosseini have chosen a convenient controller in their models which led them to reach good quality results [3]. However, FLC is recommended as an alternative for applications in real time systems based on the results proposed here and those proposed by Y. Q. Xing, J. X. Jin, Y. L. Wang, B. X. Du and S. C. Wang [11]. For the future work, the study may need to be extended with using the proposed FLC to control couple ESDs such as BESS, CAES, and FES in order to make comparison with the proposed results SMES.

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Biography

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