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Stability Enhancement of Multi-Machine Power System interconnected with Wind and PV plants Using Fuzzy Logic-based FACTS Controller

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Abstract

Grid-connected renewable energy-based generation are deploying in recent years for many economic and environmental reasons. This type of generation could have a significant impact on power system voltage stability given the nature of the primary source for generation and the technology used for energy conversion. In this paper, Fuzzy Logic-based FACTS controllers have been presented to damp the power system oscillations in the presence of the wind and PV power plants. The results of an investigation of stability in heavily stressed IEEE-9 bus test system with large-scale of Wind and PV integration have been presented to evaluate the control system. Moreover, a comprehensive comparison has been introduced to evaluate the effectiveness of the proposed controller under different conditions of operations. The comparison of fuzzy-based STATCOM performance with and without large-scale PV power plant has been introduced.

Keywords: PV plants; Wind energy system; STATCOM; fuzzy logic control; Stability

I. INTRODUCTION

In network Utilization of renewable energy comes from the perspective of environmental conservation and fossil fuel shortage. Among the renewable energy sources, the PV and Wind power plants are the primary sources of renewable energy in the world. Considering the statistical of the GLOBAL STATUS REPORT 2019 of the renewable energy REN21 [1], the Solar photovoltaics (PV) and wind are now mainstream options in the power sector. Moreover, an increasing number of countries generating more than 20% of their electricity with solar PV and wind. Global renewable power capacity grew to around 2,378 GW in 2018. For the fourth year in a row, additions of renewable power generation capacity outpaced net installations of fossil fuel and nuclear power combined. Around 100 GW of solar photovoltaics (PV) was installed – accounting for 55% of renewable capacity additions – followed by wind power (28%) and hydropower (11%). Overall, renewable energy has grown to account for more than 33% of the world's total installed power generating capacity as shown in the chart of figure 1. Considering only non-hydropower capacity, at least 45 countries have topped the 1 GW mark, while 17 countries have more than 10 GW combined of wind power, solar PV, bio-power and geothermal power. In 2018, the top countries for non-hydro capacity were China, the United States and Germany (all over 100 GW), followed by India and Japan, then the United Kingdom, Italy and Brazil/Spain. The top countries for non-hydro renewable power capacity per inhabitant were Iceland, Denmark, Germany, Sweden and Finland.195 as shown also in figure 1.

In Tokyo-Japan, during 2019, the first urban rail service in Japan to be powered entirely by renewable energy to transport 57 thousand passengers each day which powered by geothermal power and hydropower and this led to a reduction of carbon dioxide emissions by an estimated 1,263 metric tonnes per year. This motivates us to invite the countries to extend the usage of renewable energy sources like PV and wind for industrial developments.

Because the large-scale implementation of the PV and wind power plants has the commercial attractive, recently many researches groups study the impacts of these nonlinear control systems which its performance also depends on environmental conditions, on power system stability. Among the literature researches, numbers of these studies introduced the impact of the PV only [2-5] while the others presented the wind power effects [6-8]. In the other hand a few studies the influence of the PV and wind plants in the power system stability [9]. This motive us to evaluate the proposed control system considering the integration of the two renewable energy sources of PV and wind with the power system stability.

II. RELATED WORK

Among stability issues, voltage instability has been a major concern for power system [2-11]. One of the essential solutions to ensure stability is reactive power compensation during the abnormal operating conditions. Moreover, the Flexible AC transmission system (FACTS) devices such as (static synchronous compensator) STATCOM, static synchronous series compensator (SSSC), thyristor-controlled series compensator (TCSC), and AVR are the main devices which used to control the reactive power in the power systems [2-11, 29]. The PV plants also may be used and controlled to be as FACTS devices [10].

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Numerous studies are done to improve the performance of the integrated wind and PV Energy Systems (PVWES). In reference [12], the squirrel cage induction generators (SCIG) has been used in order to improve the stability of the wind energy system. The Static VAR compensator (SVR) has been used with wind energy plant to ensure voltage stability [13, 14]. Moreover, the STATCOM is employed for enhancing the transient stability of the wind power plants considering different operating conditions such as speed variations in Ref. [15]. The application of the STATCOM in the renewable energy systems to enhance transient stability has been presented in Refs. [16, 17], to mitigate the voltage fluctuations in Ref. [18] and to enhance the fault ride-through (FRT) capability of wind power plants in Ref. [19].

Many conventional techniques are proposed to control FACTS devices such as the conventional controllers as PI and PID controllers [20, 21]. However, these fixed traditional controllers have the drawback of poor performance with varying the operating conditions. The researchers are researching to introduce more intelligent controllers which can act with deferent operating points [20, 21]. The optimization techniques have been introduced to enhance the performance of such controllers but this lead to increase the implementation processes and increase the cost of hardware control systems [22]. The robust controllers such as the H infinity and sliding mode had been presented to improve the control system performance. These robust controllers also may suffer from the problem of the fixed parameters and other problems such as chattering in the sliding mode control [24, 25]. Moreover, neuro-fuzzy controllers (NFC) technique has been introduced to control STATCOM for reactive power control in the wind energy systems has been introduced in [18]. Other researchers in different processing and control engineering fields suggested the Fuzzy logic control (FLC) [7, 26]. They prove the FLC is most valid controller which may be used for regulating the different control plants under varying the operating conditions.

In this paper, a proposed control approach for enhancing the transit stability of the integrated PV and Wind energy system with the 9-bus test system has been introduced. The STATCOM based fuzzy logic controller has been applied. The proposed STATCOM based FLC has been evaluated based on Matlab/Simulink package. The PVWES with the STATCOM has been tested under different abnormal operating conditions at random locations in the system. Moreover, the impact of PV plant has been investigated.

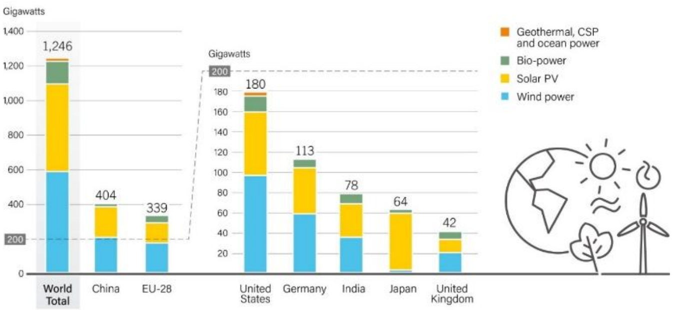

Figure 1. Renewable Power Capacities in World, EU-28 and Top 6 Countries, 2018, [1]

III. CONFIGURATION OF THE POWER SYSTEM UNDER STUDY

The nine-bus power system has been considered as the case study in this paper [27, 28]. The system has two generators, one wind farm, and one PV power plant as shown in figure 2. The data specifications of nine-bus power system without the PV or wind farm are stated in Ref. [28]. The rated of the wind farm and PV plant has been assumed to be 90MW and 80MW. A wind farm based on DFIG is fed to WSCC system instead of generator number 3 with the same generated power. WF consists of three different groups each one has 20 turbines with a capacity of 1.5 MW. Each group is connected to 575/13.8 KV transformer. The PV system has been connected to bus 5. The rating of the STATCOM is 100 MVAR. The specifications of the wind turbine and the PV are shown in Table 1 and Table 2 respectively.

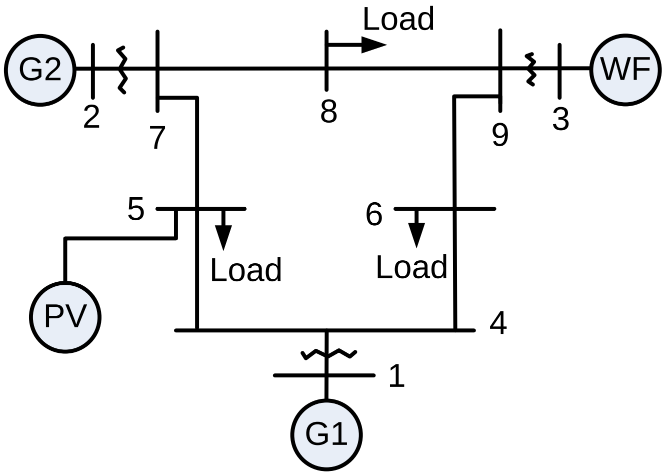

Figure 2. The configuration of the power system under study (60 Hz, 100 MVA Base)

Table 1. The parameters of wind turbine based DFIG

Generator power (MW)	1.5/0.9	Friction factor (p.u.)	0.01
Phase to phase voltage (V)	575	DC-Link voltage	1200
Stator resistance (p.u.)	0.00706	DC-Link capacitor	0.01
Rotor resistance (p.u.)	0.005	DC Battery capacity kWh	900
Stator leakage inductance (p.u.)	0.171	DC voltage regulator gains [K_p, K_i]	[0.002 0.05]
Rotor leakage inductance (p.u.)	0.156	GSC regulator gains [K_p, K_i]	[2.5 500]
Magnetizing inductance (p.u.)	2.9	RSC regulator gains [K_p, K_i]	[0.3 8]
Base frequency (Hz)	60	Pairs of poles	3

IV- FUZZY LOGIC CONTROLLER

Identification of PI controller parameters in order to enhance SVC or STATCOM performance cannot be simply done. FLC has been considered one of the nonlinear and robust control techniques based on expert knowledge and there is no need to have an accurate model of the system [26]. Fuzzification module, rule base, an inference engine and defuzzification module are essential elements of FLC as illustrated in Fig. 3 [26].

In this paper, Mamdani's type FLC has been considered since it's simple and can easily implement for controlling SVC susceptance (β) and STATCOM quadratic axis reference current (Iq*). The input to FLC is the error voltage signal and change of error. FLC output was used to integrate (Iq) in case of STATCOM and susceptance for SVC. The inputs and output membership function consist of seven linguistics of triangular type. The linguistic variables E, CE, and the controller output will take on the following linguistic values: (NB) = Negative Big; (NM) = Negative Medium; (NS) = Negative Small; (Z) = Zero; (PS) = Positive Small; (PM) = Positive Medium; (PB) = Positive Big. The FLC rules are shown in Table II [26]. It has two inputs each has seven linguistics that produces forty-nine possibilities or rules.

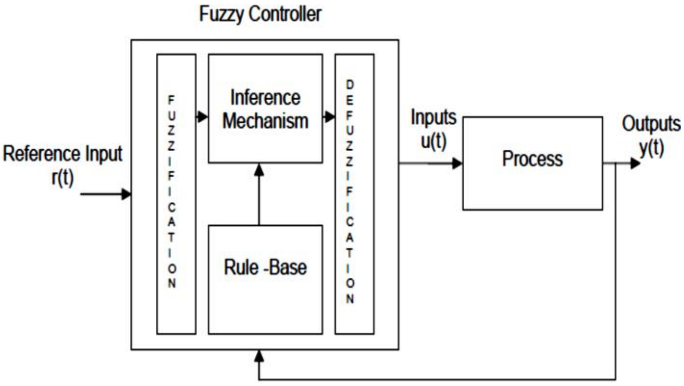

Figure 3. Essential parts of FLC

Table 2. FLC rules

E \ CE	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

V. THE STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

STATCOM is one of Shunt FACTS devices. Typically, it is applied in the power systems to enhance transient stability based on controlling the flow of the reactive power. It is fed by an energy source capacitor or energy-storage device at its input terminals [27]. In the renewable energy systems, such that considered in this paper, it is connected at the interconnected points of the renewable energy sources. The process of the STATCOM operation has been illustrated in figure 4.a). Basically, it consists of solid-state devices to control the voltage across its terminals. In Figure 4.a), the voltage V1 and V2 represent the controlled system voltage and the STATCOM generated voltage respectively. Moreover, figure 4.b) shows the schematic diagram of STATCOM construction with its integration with the three-phase grid.

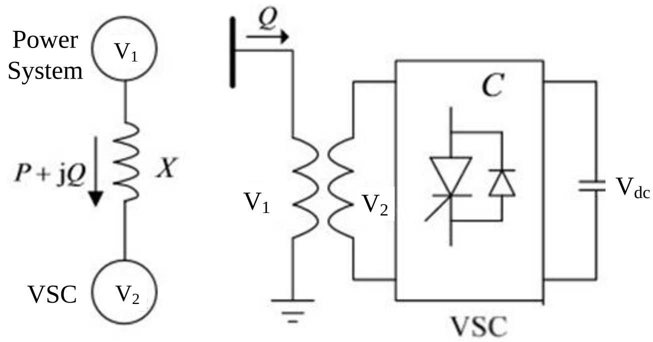

Figure 4. Operating principle of the STATCOM

At steady state, the transfer reactive power among STATCOM and the power system has been accomplished through regulating the STATCOM magnitude voltage using the following mathematical expression;

$$Q = \frac{V_1^2 - V_1 V_2}{X}$$

where;

Q_c	reactive power exchange between STATCOM and UG;
V_1	UG voltage;
V_s	STATCOM output terminal voltage;
X_{tr}	Transformer leakage reactance.

Moreover, the transfer of active power can be calculated as the following:

$$P = \frac{V_1^2 - V_1 V_2 \cos\delta}{X}$$

where δ is the angle among the V1 and V2

The block diagram of the STATCOM and its control scheme has been shown in figure 5 a). Furthermore, the VI characteristics of the STATCOM has been shown in figure 5 b). Moreover, the model of the STATCOM based FLC control scheme has been shown in figure 6. The system voltage is measured at the system point of common coupling then compared with the reference value. Then the error signal and change of error are fed to FLC that provides the reactive reference current Iqref. The STATCOM reactive current Iq is compared with Iqref, and the output of the current regulator is the angle phase shift of the PWM inverter.

VI. RESULTS AND DISCUSSION

The case study of the PVWES power system has been illustrated in figure 2. This system is integrated with STATCOM based-FLC and its Simulink model has been shown in figure 7. The system has been validated through simulation against the application of three-phase to ground faults at different locations in the power system. The results of the stability performance have been introduced in the presence and absence of the proposed STATCOM. Moreover, the impact of the PV system has been presented to evaluate its effect on power system stability.

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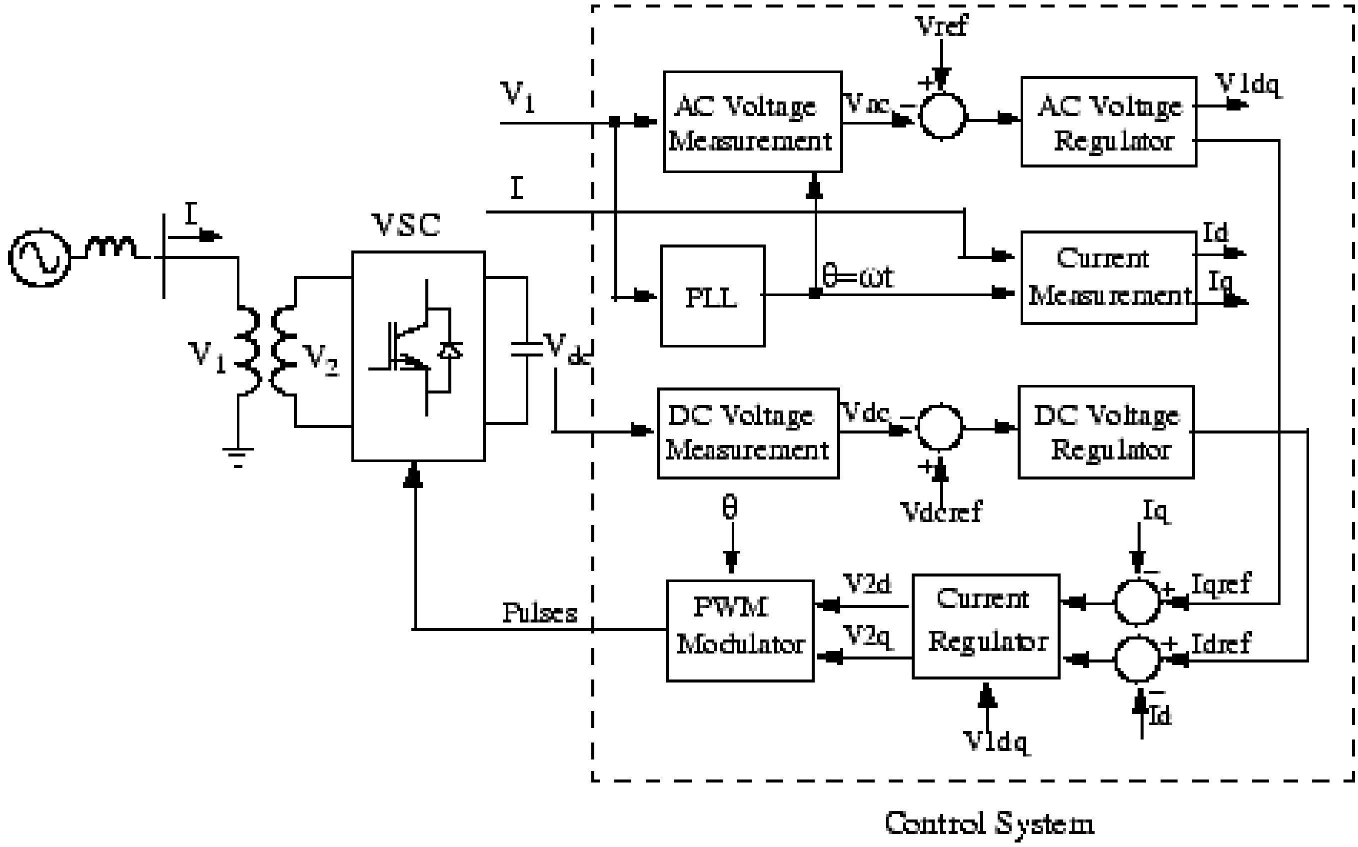
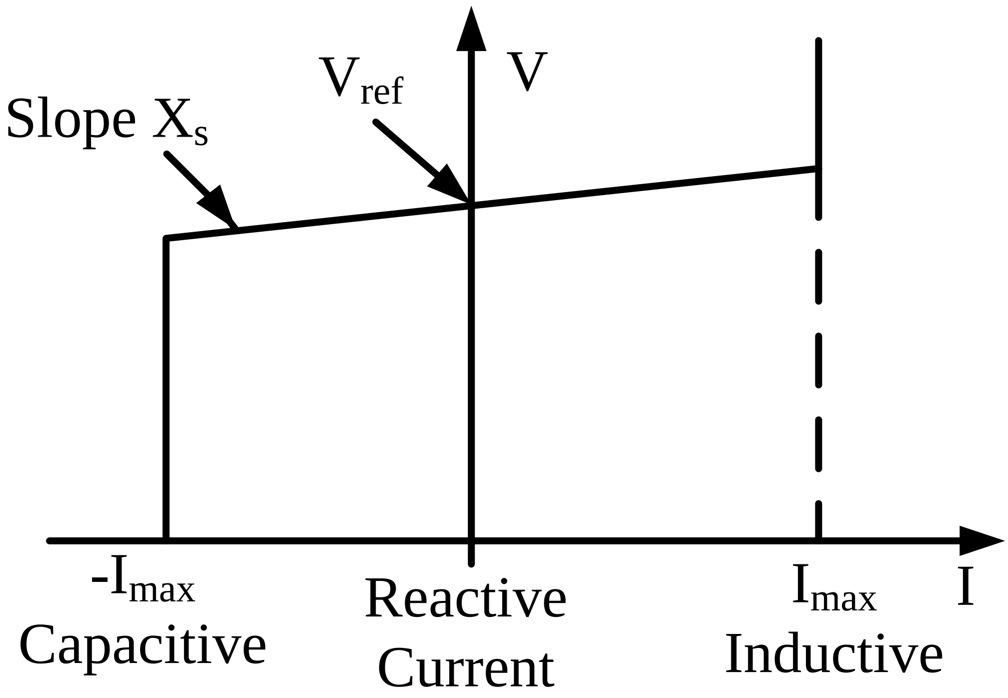


a)



b)

Figure 5. a) Diagram of a STATCOM and its control system, b) STATCOM V-I characteristic.

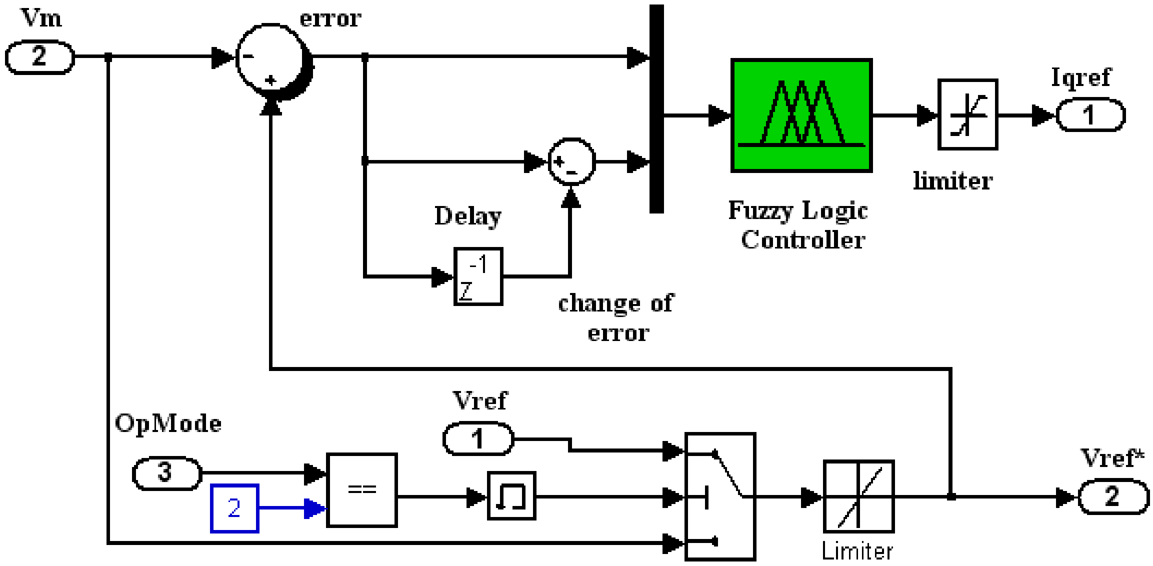


Figure 6. Matlab/Simulink model of STATCOM Based FLC

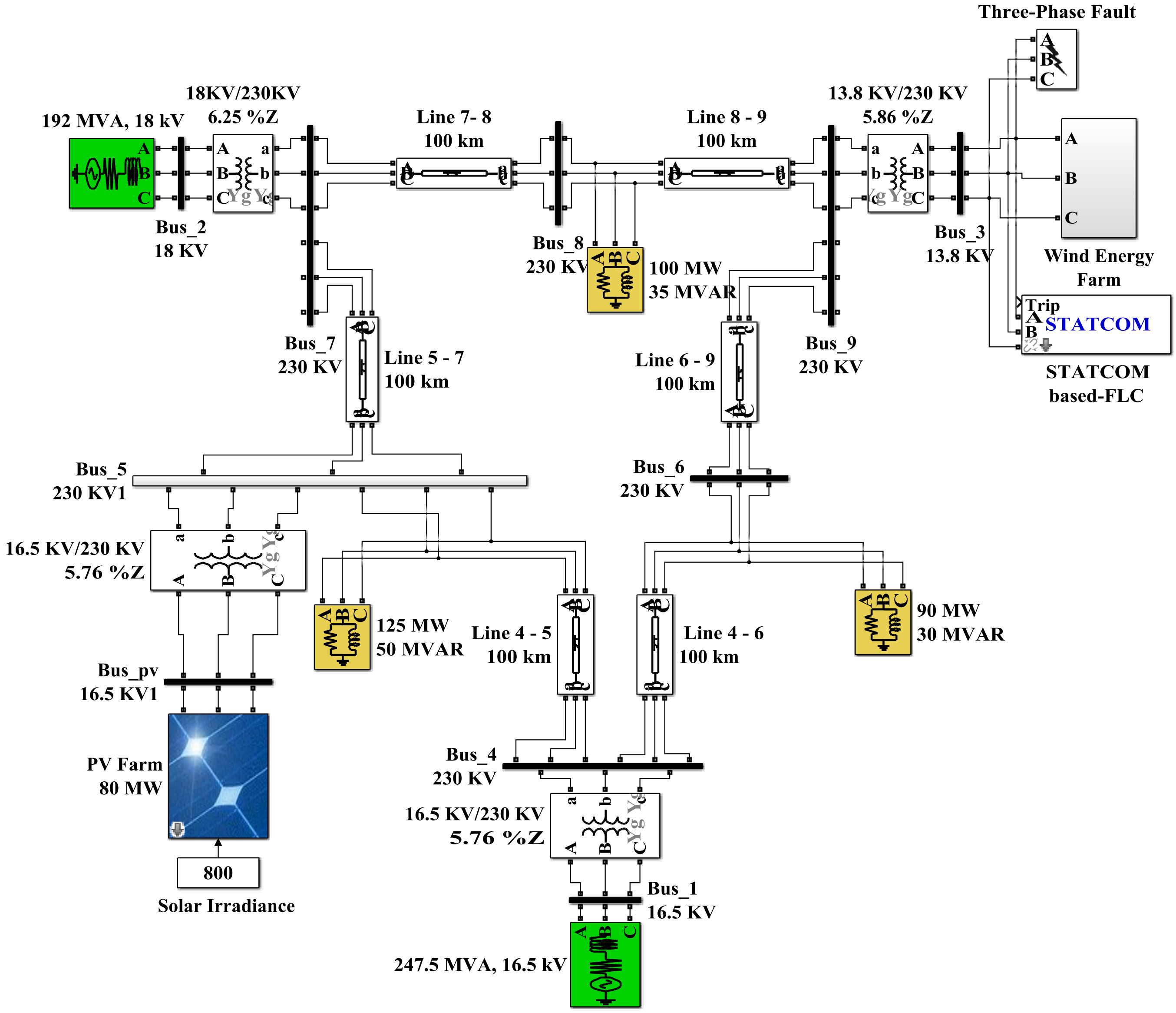


Figure 7. Simulink model of the overall studied power system

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VI.I Case 1: The Fault located at WF Bus 3

In this case of study, a 3-phase to ground fault is assumed to occur at bus 3. At this bus, the wind energy plant has been integrated with the system. Moreover, the STATCOM is connected at the same integration point. The fault has been assumed to occur at the time of 4 seconds from the simulation time and has been cleared after 0.05 second. The simulation results of such case of study have been shown in figure 8 to figure 12. The figures show the stability performance of the system in the case of using STATCOM and without it for comparison reasons. In these figures, the dashed blue line is for the case of using STATCOM. The red solid line is for the case without STATCOM. From the results of figure 8, it can be concluded that STATCOM has better time response via the performance of the system without FACTS devices. The performance of the control system with STATCOM based-FLC has a lower overshoot of 9.4 % while the performance of the system without STATCOM has overshot of 6.4%. Moreover, the system with STATCOM has smaller ripple compared to the system without STATCOM. These results have been confirmed also from the performance of the system at buses 2, 3 and 5 as shown from figures 9, 10, 11 respectively.

Furthermore, the transient response of system voltages at Buses 6, 7, 8 and 9 is shown in figure 12. The figure shows that the time response of system voltages is enhanced using STATCOM. The application of the STATCOM based FLC results in an improvement in the system performance according to the overshoot and steady-state time.

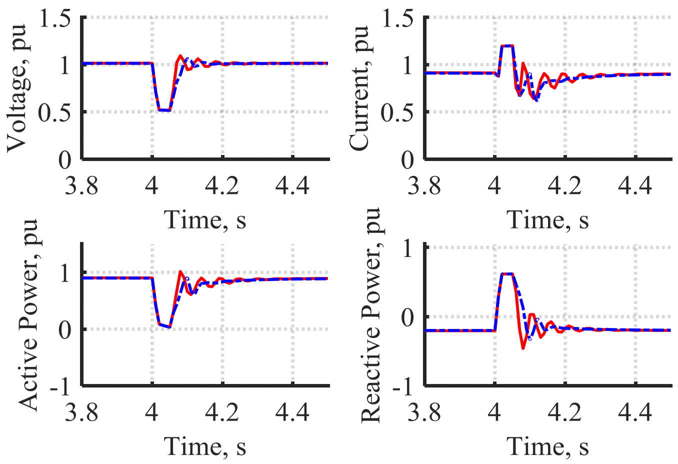

Figure 8. Dynamic time response at generator 1

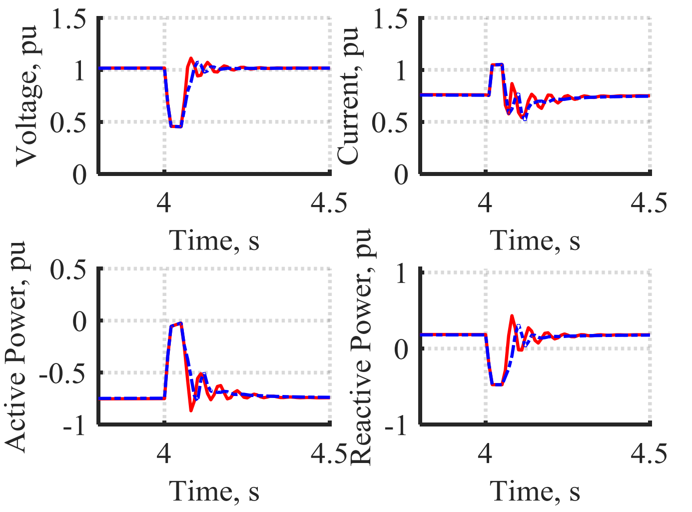

Figure 9. Dynamic time response at generator 2

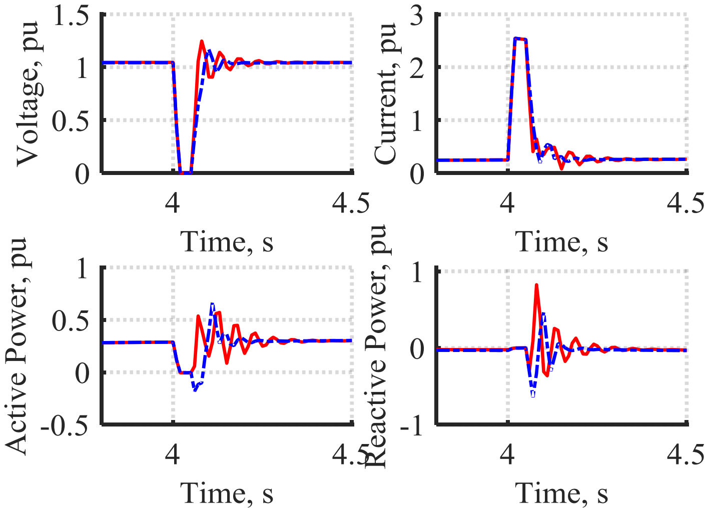

Figure 10. Dynamic time response of Wind farm at bus 3

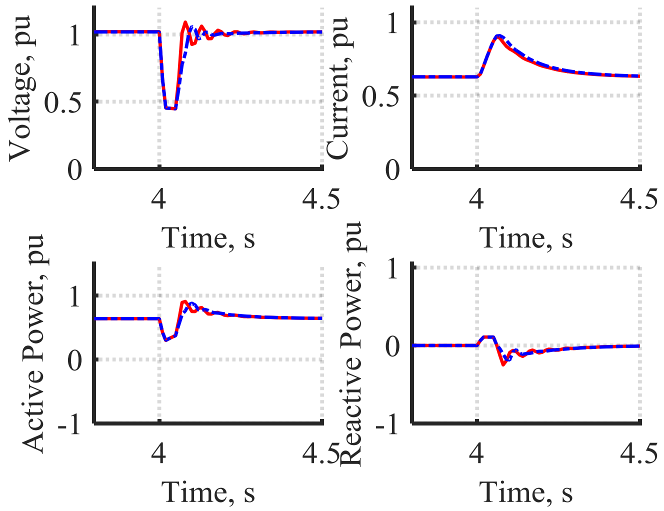

Figure 11. Dynamic time response of PV at bus 5

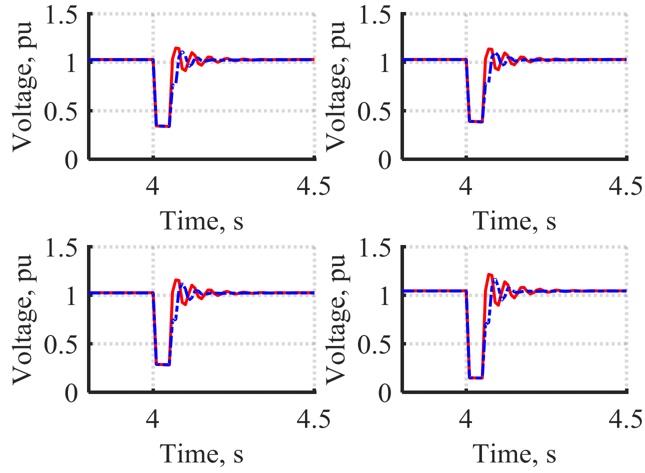

Figure 12. Dynamic time response of voltage at Buses B6, B7, B8 and B9

VI.II. Case 2: Fault located at Bus 6

Another case of study has been applied to validate the control system. In this case of study, the three-phase to ground fault has been assumed to have occurred at bus 6. The simulation results of the system stability performance have been shown in figure 13 to figure 17. From the figures, the performance of the system with STATCOM based-FLC is better than these of the system without FACTS devices. Figure 13 shows the dynamic time response of generator 1. This figure shows that the overshoot of the system with STATCOM is reduced to 3.4% while for the system without the STATCOM, the overshoot is 6.3%. These results also are confirmed from figures 14, 15, 16 for the transient performance for the generator 2 and generator 3 of the wind farm and the PV plant at bus 5.

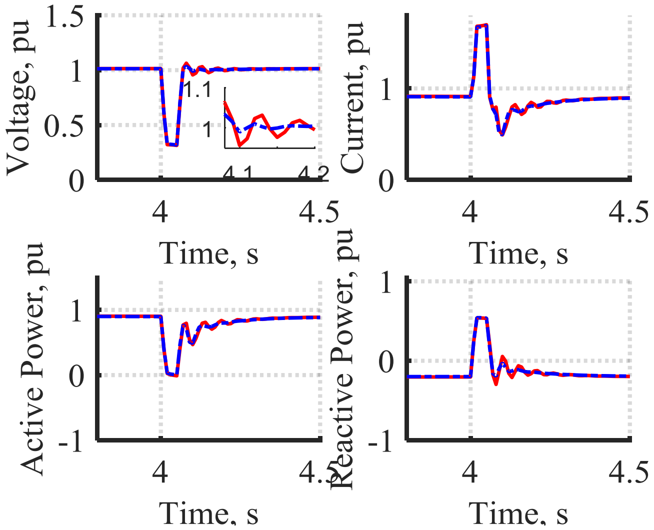

Figure 13. Dynamic time response at generator 1

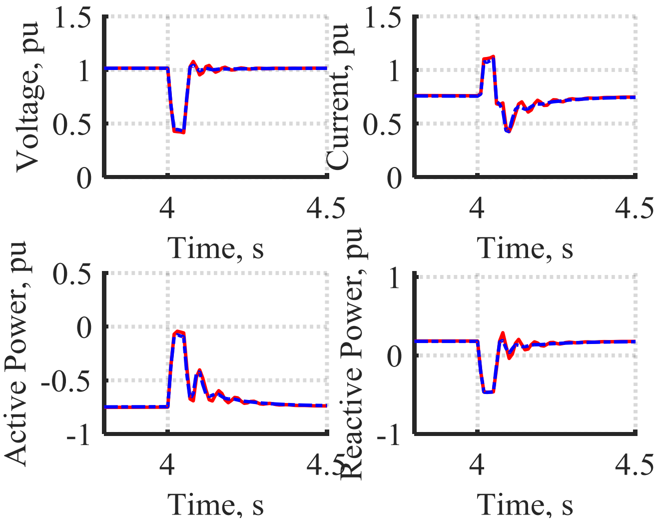

Figure 14. Dynamic time response at generator 2

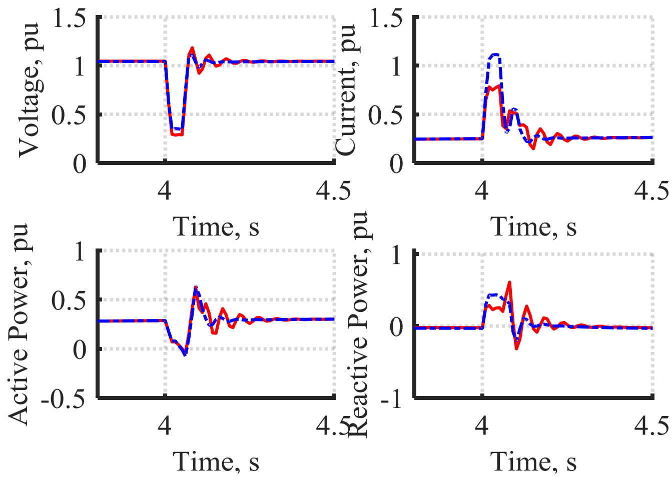

Figure 15. Dynamic time response at wind energy bus 3

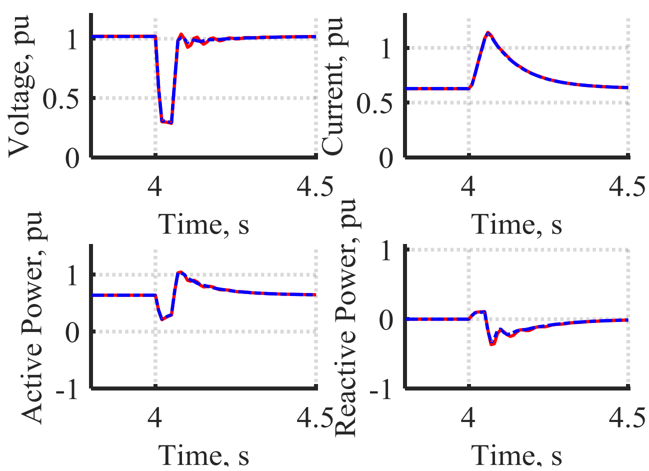

Figure 16. Dynamic time response at PV plant bus 5

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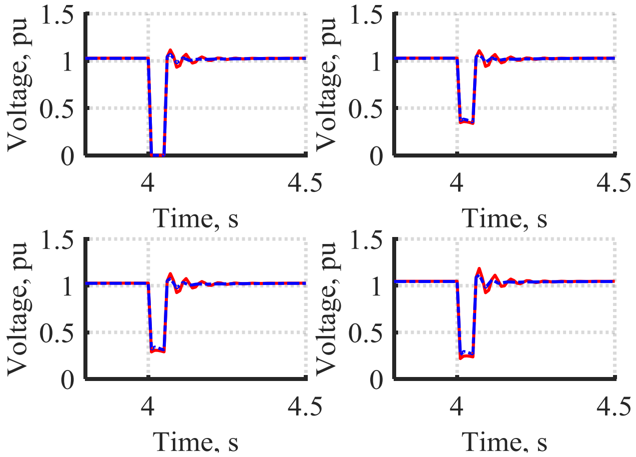

Figure 17. Dynamic time response of voltage at Buses B6, B7, B8 and B9

VI.II. Case 3. Fault at bus 3 with interconnecting and disconnecting of PV

This case of study is to investigate the impact of the PV power plant on the overall performance of the system. In this case of study, a fault is assumed to have occurred at bus 3. A comparison between the transient stability of the system integrated with the PV and without it. Figures 18 to 21 introduce the simulation results of the dynamic response of the system at busses 1, 2, and 3 respectively. Moreover, the dynamic time response of the voltage at reset busses 5, 6, 7 and 8 have been illustrated in figure 22. From the results, the integration of the PV power plan has been assisted to enhance the steady-state of the voltage, to reduce the power levels and currents at the busses of generators and wind farm which reflect the improvements of the power quality of the system. From figure 1, the voltage level at bus 1 has been enhanced at steady-state, while the transit performance is not affected in the case of the PV or without PV integration. The same results can be conducted from the system performance at the reset busses.

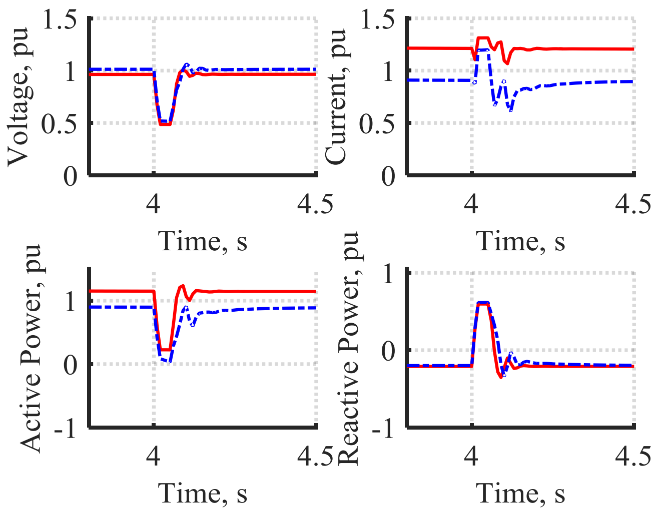

Figure 18. Dynamic time response at bus 1

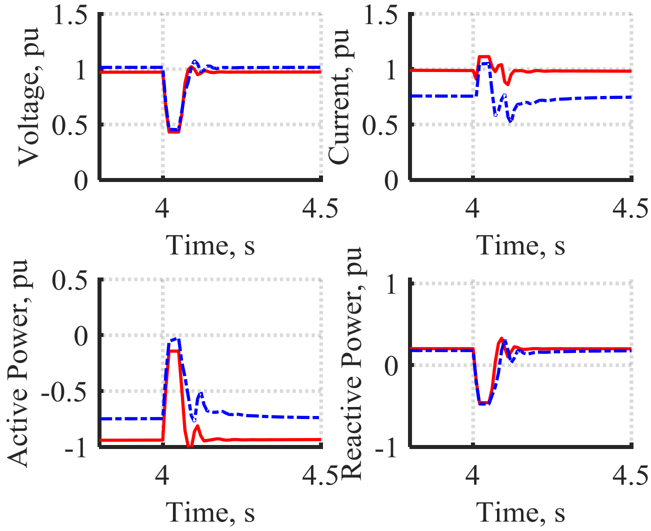

Figure 19. Dynamic time response at bus 2

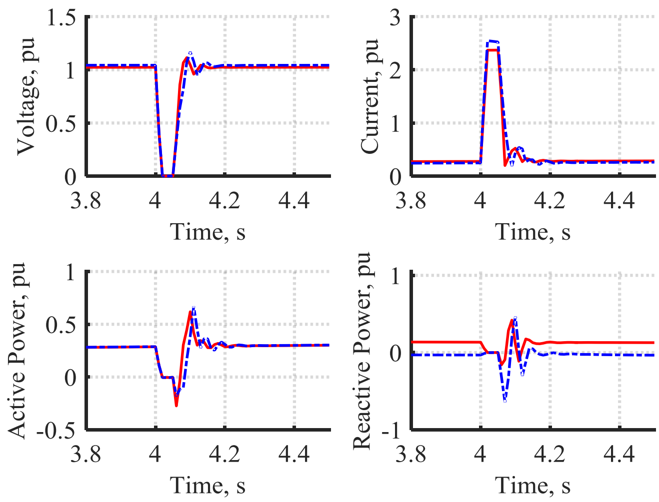

Figure 20. Dynamic time response at bus 3 of wind farm

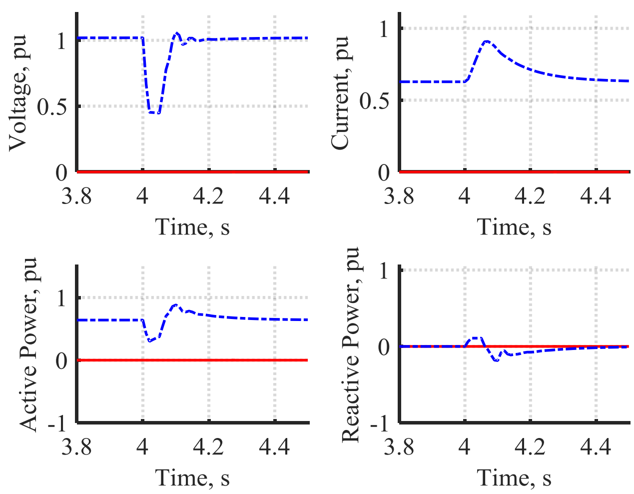

Figure 21. Dynamic time response at bus 5 of PV plant

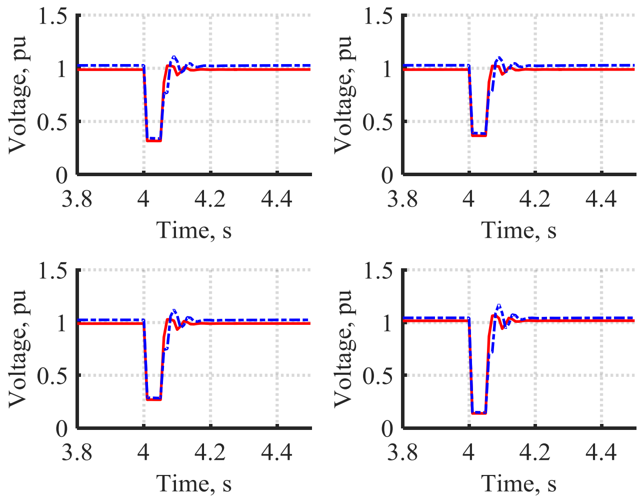

Figure 22. Dynamic time response of voltage at Buses B6, B7, B8 and B9

VII. CONCLUSION

In this paper, STATCOM based FLC application for enhancing the transit stability of the Power system interconnected with wind and PV power plants has been presented. The dynamic model of the studied power system is simulated using Matlab/ Simulink. For validation of the STATCOM based FLC, the system is endangered to three-phase to ground faults at different locations. The simulation results show that the application of the proposed FACTS device improves the transit performance of the system. Moreover, a comparison between the performance with and without STATCOM has been presented. moreover, the impact of connecting and disconnecting the PV power plant in the system performance. The results validate that the application of STATCOM based-FLC results in improving the stability of the system. Also, the Integration of the PV power plants improves the voltage level at steady state while the trainset stability performance of the power system using STATCOM based-FLC is not reduced with or without the PV plants.

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