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Voltage Stability Analysis of a Large Scale PV Plant for Different Control Options

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Abstract

The increasing integration of photovoltaic (PV) plants into conventional power systems has led to the need to examine the effects of these plants on the system dynamics. By considering this increasing integration rate, in this study, a well-known IEEE-9 bus power system is modified by adding a PV plant in DigSilent Powerfactory environment. Three different transient cases are tested by using PV plant control units designed by Western Electricity Coordinating Council (WECC). The effect of the load and line transient disconnections and 3-phase short circuit fault on modified power system are investigated as case-I, case-II, and case-III, respectively. In all cases, two sub-cases are considered according to the location as a distance factor. As a result, comparison of PV different control options (DCO) is done in terms of voltage stability for these 3 cases and the obtained results are discussed in detail.

Keywords: Reactive power control methods, IEEE-9 bus power system with large scale PV integration, voltage stability, 3-phase short circuit fault, transient line and load disconnection, distance factor

1. INTRODUCTION

Due to the developing technology, increasing demand in energy consumption and the necessity of the clean energy of future, renewable energy sources expands their energy generation area day by day. Considering the part of energy production among the renewable energy sources, it can be definitely said that the PV power plants are one of the most popular source [1].

Some differences between the PV plants and conventional energy sources in terms of energy generation methods occurs. There are some disadvantages of PV plants in energy generation such as the effect of reducing the total moment of inertia of the power system and being affected by weather conditions directly [2, 3]. On the other hand, their ability of distribute generation and voltage and frequency control through power electronic control units reveals the advantages of the PV plants. Therefore, it is important to examine the PV plant effects on the power system dynamics based on stability and sustainability.

It is seen from the literature that there are stability studies containing the effect of the PV plants on the power systems for various type of situations. Generally, it is possible to classify these studies as frequency stability, rotor angle stability, and voltage stability [4, 5].

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In the investigation of the voltage stability of PV plants, it is generally studied that PV plants are integrated to traditional power systems [6-10]. On the other hand, integration of PV plant with wind power systems are also available [11-13]. Voltage stability studies of PV plant integrated power systems contain consideration of different reactive power support methods [8], solar radiation, temperature and load changes [9], conventional and developed dynamic voltage support (DVS) [10], low voltage ride through (LVRT) [14], different penetration levels [15, 16], central and distributed generation [16], different constant power factors and automatic voltage control [17], one or more PV plant with connected to the same bus [18], reactive power compensation system [19] and so on. Stability studies by comparing the DCO of the PV power plants designed by WECC is rarely analyzed in literature [7, 20]. In these studies, voltage stability in short circuit fault and small signal stability are investigated, respectively.

The PV plants can be integrated to the power systems through WECC PV plant model [21]. It has been observed from the reported studies in the literature that there are limited studies to compare the DCO modeled by WECC. In the light of this motivation, the effect of DCO are need to be investigated in terms of voltage stability by considering different cases.

In this study, the effects of PV plants on voltage stability for different control options have been analyzed in detail by considering different conditions such as transient disconnection of the load, transient disconnection of the line, and 3-phase short circuit fault. In addition, the location of the fault with respect to the PV plant is also studied in this paper. In this manner, a well-known IEEE 9-bus power system has been modified by connecting a PV plant instead of G3 generator for the Bus-3. The whole power system is simulated in DigSilent Powerfactory program and the obtained results are discussed in detail in Section III and IV, respectively.

The organization of this study is given as follows. Voltage stability analysis and modelling of the modified power system are presented in Section II. Considered cases and simulation results with comparative analysis are illustrated in Section III. Finally, conclusion is stated in Section IV.

2. VOLTAGE STABILITY AND POWER SYSTEM MODELLING

2.1. Voltage stability

Voltage stability generally can be expressed as the ability of the power system to maintain the scheduled voltages of all buses in case of disturbance [5]. It depends on keeping the equilibrium between load demand and supply. The voltage stability criterion can be demonstrated as shown in Fig. 1 by separating active power and reactive power demands. In Fig. 1, $[P_L(V)\ ,Q_L(V)]$ and $[P_S(V),\ Q_S(V)]$ are the active and reactive power of the load and supply, respectively [22].

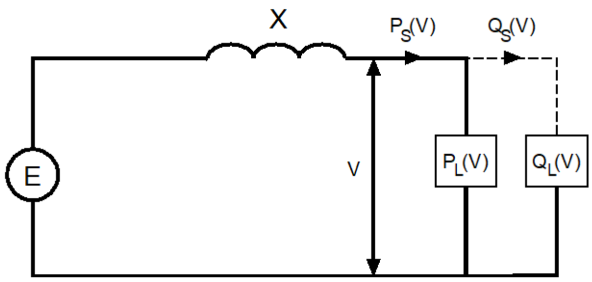

Figure 1 Equivalent circuit of the separated presentation of active and reactive power [22]

In normal operating conditions, $P_L(V)$ is equal to $P_S(V)$ and $Q_L(V)$ is equal to $Q_S(V)$. However, the relationship between the reactive power of the load and supply can be considered separately for voltage stability analysis. It is also assumed that the load is not determined by the reactive power demand. The active and reactive power equations are given below.

$$P_L(V) = P_S(V) = \frac{EV}{X}\sin\delta \tag{1}$$

$$Q_S(V) = \frac{EV}{X}\cos\delta - \frac{V^2}{X} \tag{2}$$

where E is the voltage of the supply, V is the voltage of the load, and X and δ are the total reactance and angle between the supply and load voltages, respectively. By considering $(sin^2\delta + cos^2\delta = 1)$, (3) can be written by using (1) and (2).

$$\left(\frac{EV}{X}\right)^2 = {P_L}^2(V) + [Q_S(V) + \frac{V^2}{X}]^2 \quad (3)$$

The final equation (4) which defines the reactive power-voltage characteristic can be obtained from (3) as follow [22].

$$Q_S(V) = \sqrt{[\frac{EV}{X}]^2 - [P_L(V)]^2} - \frac{V^2}{X} \quad (4)$$

2.2. Power system modelling

In this study, the IEEE 9-bus power system has been modified by integrating a PV plant to the Bus-3 in DigSilent Powerfactory simulation environment. The modeled power system schematic is shown in Fig. 2. In the modified model, G1 and G2 generators have a governor and automatic voltage regulator (AVR). The considered governor and AVR types are HYGOV and AVR EXAC1 for G1 generator, GAST and AVR IEEET1 for G2 generator, respectively. A detailed system model can be accessed in [23].

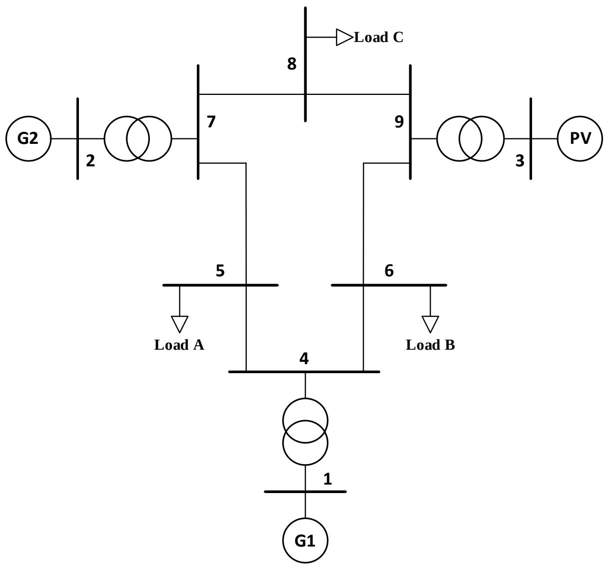

Figure 2 The modified IEEE 9-bus power system

In the studied model, generator power and voltage values are given in Table 1 and load values are given in Table 2. The bus connected to the G1 generator is selected as the slack bus, and the angle of the voltage of this bus is set to 0º.

Table 1 Power and voltage values of the sources

Sources	Bus no	Operating power (MW)	Nominal power (MVA)	Voltage (pu)
G1	Bus 1	-	260	1.040
G2	Bus 2	90	150	1.025
PV	Bus 3	140	150	1.000

Table 2 Power values of the loads

Load types	Bus no	Active power (MW)	Reactive power (MVA)
Load A	Bus 5	160	260
Load B	Bus 6	80	150
Load C	Bus 8	140	150

2.3. PV plant modelling for DCO

The integration of PV power plants into the power systems is accomplished via control units. In the integration, the power capacity of the PV plant is an important issue for the control. Considering the capacities of the PV plants, three different types can be categorized as small scale, medium scale and large scale [24]. Large scale PV plants can produce more than 20 MW active power [24]. In this study, a large scale PV plant has been modeled using WECC control modules. The WECC control modules used in this study are Renewable Energy Generator Convertor (REGC_A), Renewable Energy Electrical Control (REEC_B), Renewable Energy Plant Controller (REPC_A) [25]. The structure of the control block diagrams with sub-control units are presented in detail in Fig. 3.

There are different type DCO that can be applied by setting the flags on the WECC control modules. In order to set DCO, *pfflag*, *vflag* and *qflag* flags are arranged in REEC_B module, while *refflag* flag is set in REPC_A module. The most used DCO are tabulated in Table 3 [4] and the parameter and flag values of the REGC_A, REEC_B and REPC_A modules used in this paper are given in [26]. Also, LVRT is used in the PV plant model to ensure the connection of the power in case of a voltage drop [27]. In addition, the PV plant restores its active power at a rate of 100% of its nominal active power per second after the fault is clear. To use this feature, the parameter *rrpwr* in the REGC_A module is set to 1.

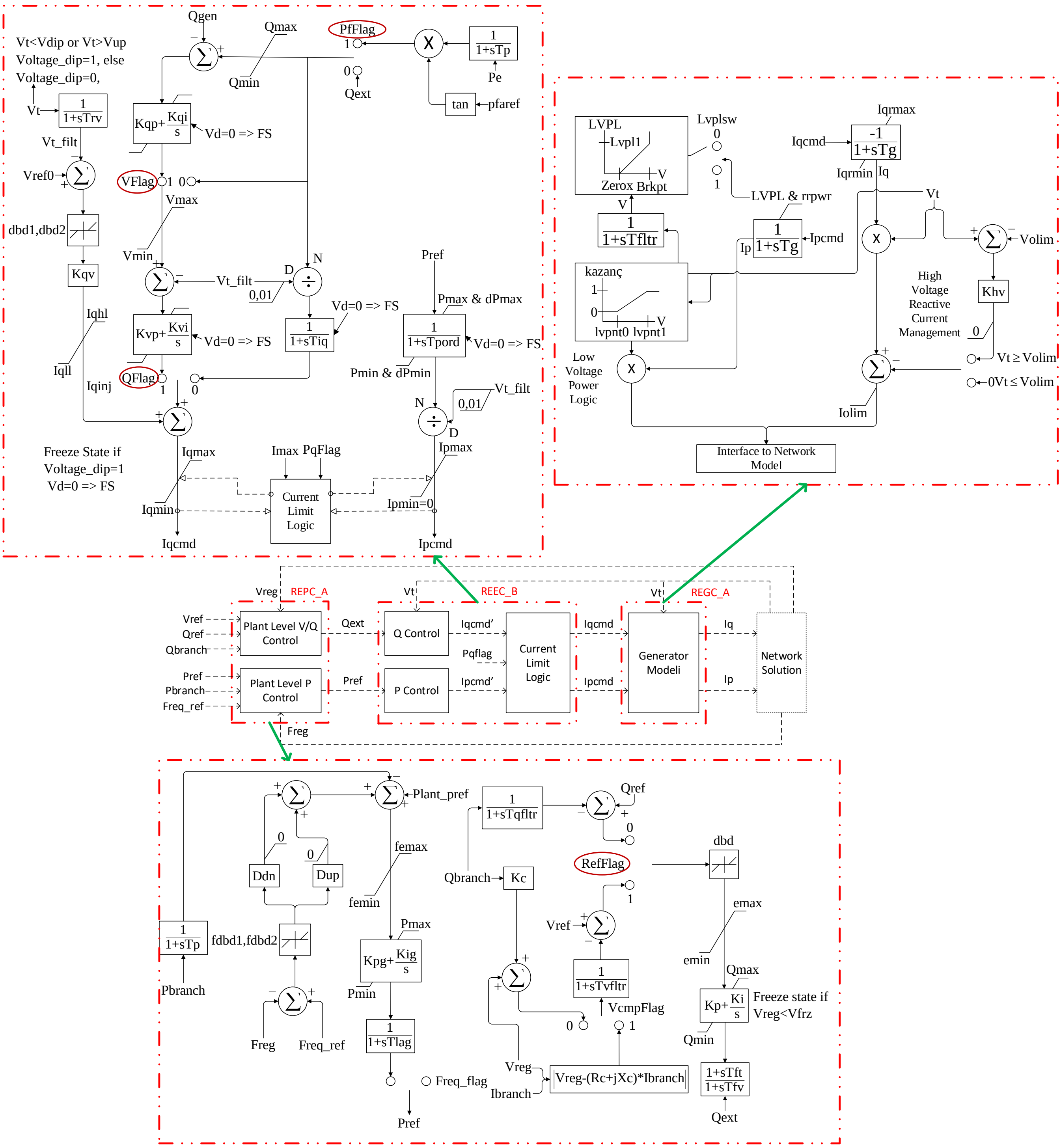

Figure 3 Control block diagram of the WECC generic central station PV system model [25].

Table 3 Type of the DCO.

Required Models	**(CLPFC)**	**(CLQC)**	**(LVC)**	**(LCQ/VC)**	**(PLQC)**	**(PLVC)**	**(PLQC& LCQ/VC)**	**(PLVC& LCQ/VC)**
Required Models	REEC_B	REEC_B	REEC_B	REEC_B	REEC_B + REPC_A	REEC_B + REPC_A	REEC_B + REPC_A	REEC_B + REPC_A
pfflag	1	0	0	0	0	0	0	0
vflag	1	1	0	1	1	1	1	1
qflag	0	0	1	1	0	0	1	1
refflag	N/A	N/A	N/A	N/A	0	1	0	1

CLPFC: Constant local power factor control, *CLQC*: Constant local Q control, *LVC*: Local V control, *LCQ/VC*: Local coordinated Q/V control, *PLQC*: Plant level Q control, *PLVC*: Plant level V control, *PLQC & LCQ/VC*: Plant level Q control & Local coordinated Q/V control, *PLVC & LCQ/VC*: Plant level V control & Local coordinated Q/V control. (More detailed explanations are available in [25, 26, 28]

PV plants can inject reactive power to the system to prevent deterioration in short-term voltage stability [10]. This feature is defined as DVS. If the voltage values specified in the REEC_B module exceeds to its nominal value, DVS is activated. The *kqv* parameter should be adjusted to activate this feature. It is recommended to select *kqv* value between 0 and 10 in the module [29]. If *kqv* parameter is set to 0, the DVS is disabled. Higher selection of the *kqv* value results to decrease the voltage drop and to increase the overshoot value because of reactive power transfer during the transient event. Therefore, the *kqv* value is set to 2 in this study. In addition, over voltage (V_{up}) and under voltage (V_{dip}) points in this study are determined as 1.1 pu and 0.9 pu, respectively. The DVS is activated for all cases in this study.

3. SIMULATION RESULTS

While analyzing the effects of the power system components on the system dynamic, it is important to consider different type unexpected cases. In this manner, the effect of DCO of the PV plant for different cases have been observed in this study. In all cases, considered transient events are applied at t=1 s and ended at t=1.1 s. The investigated voltage stability for all cases are achieved with the voltage measurement on Bus-9 which connected to PV plant via station transformer. The considered cases are given in Table 4.

Table 4 The all cases on modified power system

Case	**Transient event**	**Location of the transient event**
I	Disconnection of the load	Load A
		Load B
II	Disconnection of the line	Line 5-7
		Line 6-9
III	3-Phase short circuit fault	Bus 5
		Bus 6

In the cases given in Table 4, 2 sub-cases of 3 cases are investigated to observe the effect of the distance factor from the PV plant. The sub-cases are separately considered as given below.

3.1. Case I: transient disconnection of the load

In this case, the transient disconnection of the Load A and Load B shown in Fig. 2 has been analyzed. While Load A is located far away from the PV plant, Load B is located close to the PV plant. The reactive power demand of the Load A is twice of the Load B. In Fig. 4-5 and Fig. 6-7, voltage and reactive power with the transient disconnection of Load A and Load B are illustrated, respectively.

It can be concluded from the Fig. 4-6 that the highest voltage is obtained in the order of PLQC, CLQC, CLPFC and PLVC control modes. The control modes with the lowest voltage are LVC, PLVC&LCQ/VC, LCQ/VC and PLQC&LCQ/VC, respectively. The control modes with the least voltage deviation are LVC, PLVC&LCQ/VC, LCQ/VC and PLQC&LCQ/VC, respectively.

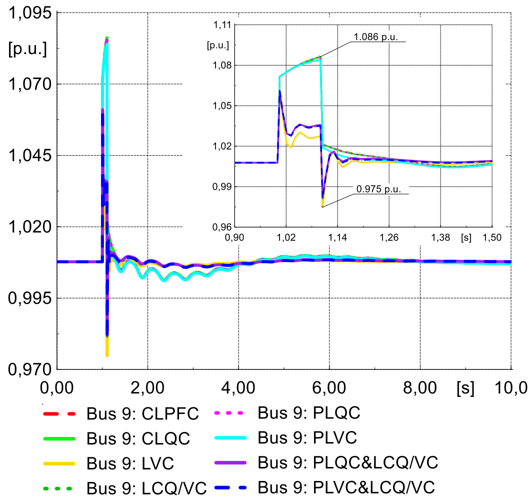

Figure 4 Voltage of the Bus-9 under transient disconnection of the Load A

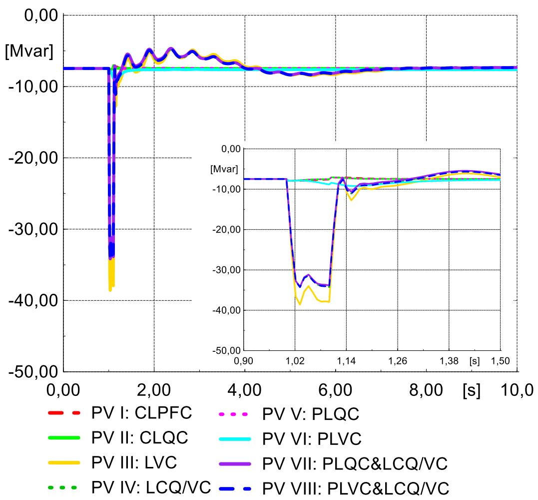

Figure 5 Reactive Power of the PV Plant under transient disconnection of the Load A

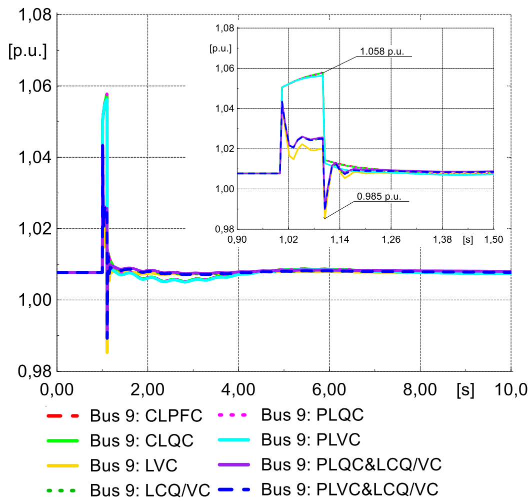

Figure 6 Voltage of the Bus-9 under transient disconnection of the Load B

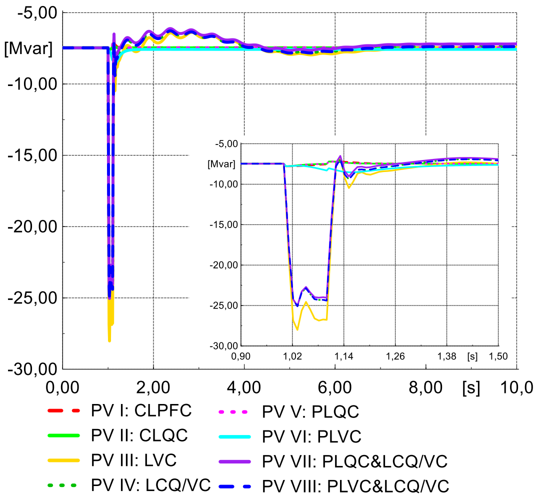

Figure 7 Reactive Power of the PV Plant under transient disconnection of the Load B

The voltage response shown in Fig. 4-6 are provided by the reactive power response of the PV plant in Fig. 5-7 to control the voltage. It is clear from the figures that reactive power response of the PV plant deviates the most in the modes with the least deviation in voltage.

As a result, the responses of the control modules in both load locations seem similar. However, the reactive power demanded by the loads is not equal and the maximum and minimum peak values are different from each other.

3.2. Case II: transient disconnection of the line

In this case, the transient disconnection of Line 5-7 and Line 6-9 seen in Fig. 2 has been analyzed. While line 5-7 is far away from the PV plant, Line 6-9 is located close to it. Voltage and reactive power responses under the transient disconnection of Line 5-7 is shown in Fig. 8 and 9, respectively.

In case of the disconnection of the Line 5-7, the reactive power supplied by G2 generator to Load A has been eliminated. As a result, the total reactive power supplied by the G2 generator during the transient event is dropped to 97.6% for the PV central reactive power control modes CLPFC, CLQC, PLQC and PLVC; 91.1% for LCQ/VC, PLQC&LVQ/VC and PLVC&LVQ/VC; 90.2% for LVC. On the other hand, G1 generator increases reactive power generation to compensate the elimination of reactive power from Line 5-7.

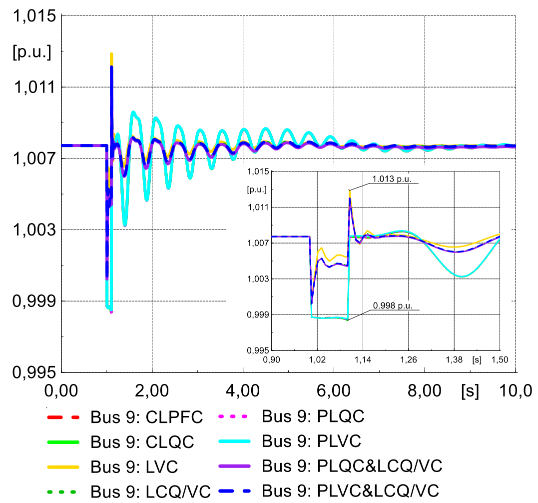

Figure 8 Voltage of the Bus-9 with the deactivation of Line 5-7

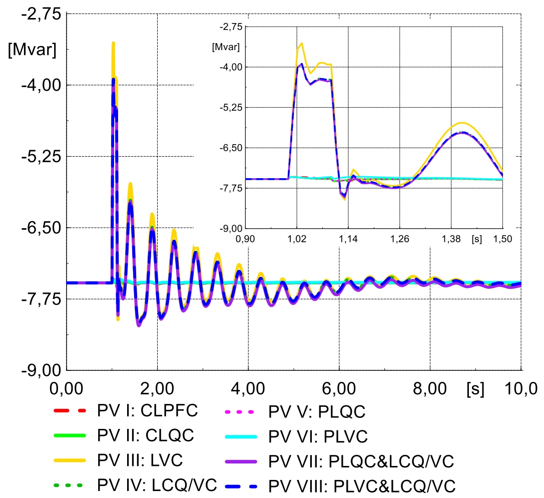

Figure 9 Reactive power of the PV plant with the deactivation of Line 5-7

In Fig. 8, the oscillation in the voltage response after the line disconnection is occurred due to the oscillation in the reactive power generation of the G2 generator. However, there is not much reactive power oscillation in the G1 generator. The effect of reactive power oscillation in the G2 generator on the Bus-9 is responded by the reactive power modes LVC, LCQ/VC, PLQC&LVQ/VC and PLVC&LVQ/VC. It results that the voltage oscillation is reduced. In the other modes, more oscillation is observed as seen from the Fig. 8 and 9.

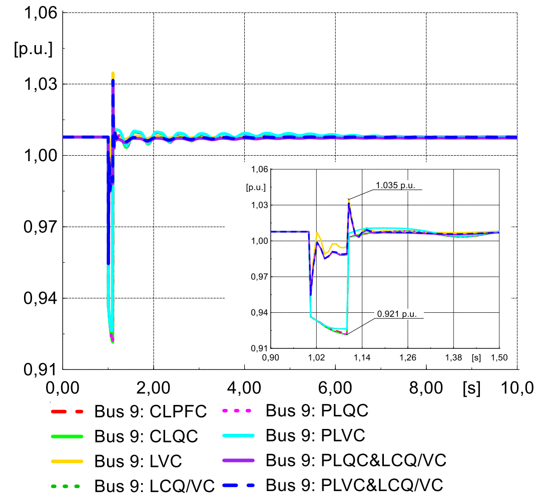

Figure 10 Voltage of the Bus-9 with the deactivation of Line 6-9

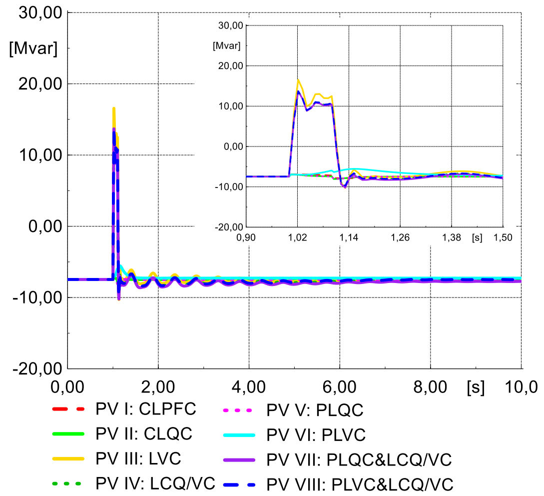

Figure 11 Reactive power of the PV plant with the deactivation of Line 6-9

In Fig. 10 and 11, the voltage and reactive power in case of transient disconnection of the Line 6-9 are given. With the disconnection of the Line 6-9, the reactive power supplied to Load B is eliminated. The G1 and G2 generators have performed more to balance the reactive power demand. After the transient event, there is not much oscillation in reactive power of the G1 and G2 generators. DCO of PV plant; LVC, LCQ/VC, PLQC&LVQ/VC and PLVC&LVQ/VC reacts against the decrease in the voltage response shown in Fig. 10 in order not to deviate the voltage from the nominal value.

In Fig. 8 and 10, the control modes of which the voltage has the highest values are LVC, PLVC&LCQ/VC, LCQ/VC and PLQC&LCQ/VC, respectively. The control modes with the lowest voltage value are PLQC, CLQC, CLPFC and PLVC, respectively. In addition, the control modes LVC, PLVC&LCQ/VC, LCQ/VC and PLQC&LCQ/VC provides the least voltage deviation.

As a result, it has been observed that the response of the control modules with the disconnection of the close (Line 6-9) or remote (Line 5-7) lines to the PV plant under the fault seems similar.

The disconnection of the remote line after the transient event causes oscillation in the voltage response. However, the close line almost causes any oscillation.

In this sub-case, LVC, PLVC&LCQ/VC, LCQ/VC, and PLQC&LCQ/VC are performed more to balance the oscillation in voltage response. Because of the differences in the power flows and locations of the lines, it results to differ peak and deep values in the responses.

3.3. Case III: 3-phase short circuit fault

In this case, 3-phase short circuit fault in Bus-5 and 6 shown in Figure 2 has been analyzed. The Bus-6 is located close to PV plant while the Bus-5 is far from the PV plant. The voltage and reactive power responses with the considered fault in Bus-5 and Bus-6 are indicated in Fig. 12-13 and Fig. 14-15, respectively.

In Fig. 12 and 14, the control modes with the highest voltage value are obtained by LVC, PLVC&LCQ/VC, LCQ/VC and PLQC&LCQ/VC, respectively. On the other hand, the lowest voltage values are provided by PLQC, CLQC, CLPFC and PLVC, respectively.

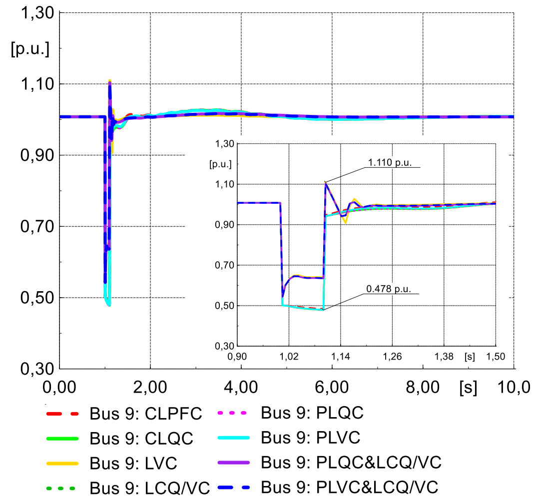

Figure 12 Voltage of the Bus-9 under the 3-phase short circuit failure in Bus-5

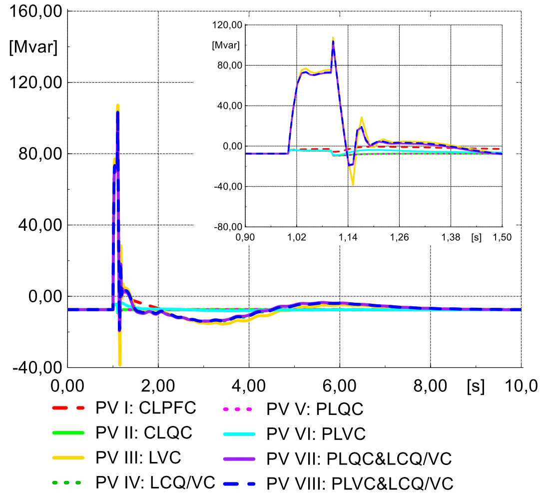

Figure 13 Reactive power of the PV plant under the 3-phase short circuit failure in Bus-5

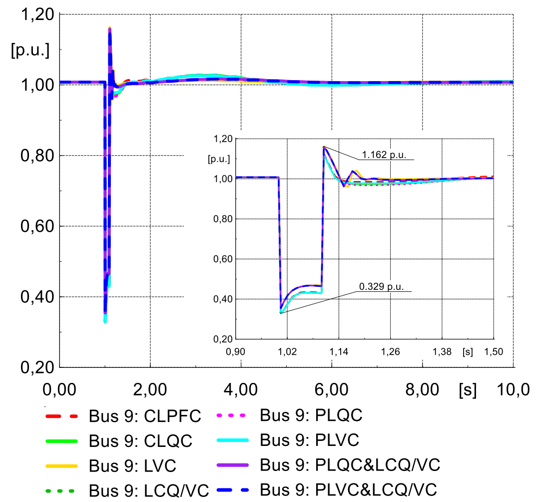

Figure 14 Voltage of the Bus-9 under the 3-phase short circuit failure in Bus-6

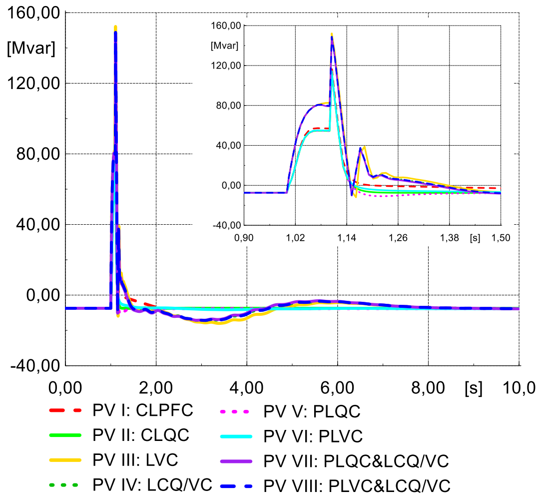

Figure 15 Reactive power of the PV plant under the 3-phase short circuit failure in Bus-6

It is known that the voltage value of the bus where 3-phase short circuit fault occurs can drop to zero. Therefore, the fault in close bus (Bus-6) to the PV plant results further decrease in the voltage of the Bus-9. At this point, the PV plant provides more reactive power to the 3-phase short circuit fault in Bus-6. It causes the voltage value of the Bus-6 is higher than Bus-5 after the fault.

In both short circuit faults on Bus-5 and Bus-6, since the voltage limit of DVS exceeds, DVS is activated. Therefore, the dynamic responses seem similar in all control modes.

4. RESULTS

Because of the increasing integration of the PV power plants into the conventional power systems, it becomes more important to analyze the effect of these plants on power systems. In this study, the effect of the DCO of the PV plant in terms of the voltage stability are investigated in IEEE 9-bus power system. Three cases with their two sub-cases are considered for the test system. The sub-cases are considered for the distance factor (close or remote to the PV plant). The obtained results of the studied cases are summarized below.

- In case I, it is observed that the responses of the DCO according to the position of the load is similar. But the magnitude of the response changes with the size of the load.
- In case II, it is seen that DCO show similar dynamic responses according to the position of the line during the considered transient event. After the transient event, the deviations in voltage are observed in remote location. Therefore, DCO incorporating local voltage control performs more to compensate the oscillation in the remote event. In addition, the difference in position has affected the maximum and minimum values of the voltage.
- In case III, it is again observed that DCO show similar responses according to the location of the fault considered in this case. However, if the fault location is close to the PV plant, the voltage on Bus-9 drops more. It results that the reactive power generation of the PV plant is increased more in remote fault (Bus-5).

In addition, two highlighted results of this study are given as follows.

- It is determined that DCO with local voltage control have more effective responses on voltage.
- When the DVS is activated, all reactive power control modes behave similarly in dynamic response.

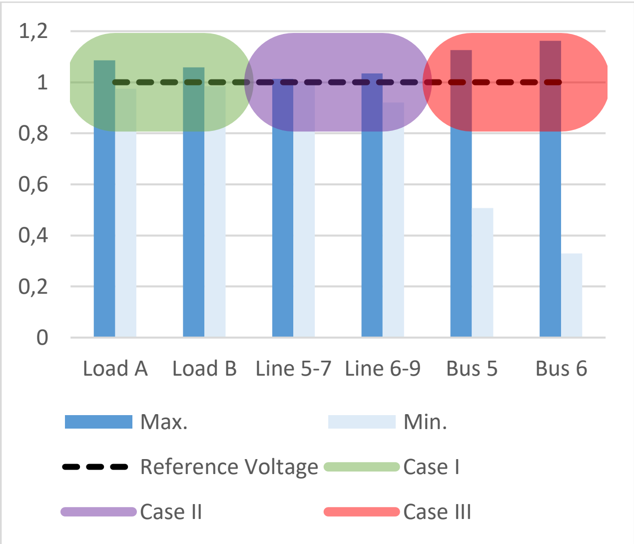

Figure 16 The obtained peak and deep voltages in cases

Finally, the peak and deep voltage values of the considered cases are shown in Fig. 16. In Fig. 16, the minimum and maximum points do not deviate in Case I and II. However, in Case III, the voltage deviation is higher than the nominal value.

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The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the authors.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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