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Photovoltaic (PV) Contribution to the Primary Frequency Control

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الملخص: تقنية الخلايا الفولتضوئية هي الأكثر كفاءة والأقل تكلفة من بين انواع الطاقه المتجدده المتاحه حاليا في السوق. ربط عدد كبير منها بشبكة القدره الكهربائيه قد يؤثر على استقرار التردد والجهد في منظومة القدره الكهربائيه. هذه الورقه تقترح طريقة تحكم في التردد والحمل لمنظومه كهربائيه تحتوي على مشاركه عاليه من الخلايا الفولتضوئية . نظام التحكم المقترح نفذ واختبر بنجاح باستخدام DACPS/EMTDC. وتناولت هذه الدراسه بالتفصيل أثر الخلايا الفولتضوئية على استقرار تردد منظومة القدره الكهربائيه. وقد تبين أن نسبة انتشار واسعة من الخلايا الفولتضوئية في الشبكه الكهربائيه مع نظام التحكم المقترح للحمل والتردد له تأثير كبير على ضمان استقرار ومستوى أمن الشبكة الكهربائية.

Abstract: Photovoltaic (PV) technology is among the most efficient and cost effective renewable energy kinds currently available on the market. The connection of a large number of PVs to the grid may influence the frequency and voltage stability of the power system. This paper proposes load-frequency control technique for system with high penetration of Photovoltaic (PV). The proposed controller has been successfully implemented and tested using PSCAD/EMTDC. In this study, the impact of Photovoltaic (PV) on frequency stability of the system is studied in detail. This study shows that large penetration of Photovoltaic (PV) with load and frequency control has a significant impact on the stability and security level of electrical network.

***Keywords*:** Photovoltaic (PV), Load-frequency control, Frequency stability.

1. INTRODUCTION

Photovoltaic (PV) technology has become one of several promising alternatives for use in energy technology. Nowadays PV systems are available from major manufacturers in a number of standard sizes with solar panels, and may be specified to be connected to the grid [1]. PV systems may be ground or roof mounted, or on the side of a building. The connection of a large number of Photovoltaic (PV) units to the grid may influence the frequency and voltage stability of the power system. Frequency stability means the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load [2]. System frequency is generally regulated through primary and secondary frequency controls. Primary frequency control (PFC) regulates the system frequency in a dynamic process, but the secondary frequency control regulates the frequency as close as its nominal value by adjusting the loads of units participating in the system frequency control [3, 4].

Many researches [4-16] have been studying the impact of DG on the system frequency, but there is no study that proposes load – frequency control on the distribution level with PV connection .This paper describes the design and implementation of the control technique for load-frequency control for system with high penetration of Photovoltaic (PV) units. The control includes facility for discrimination between normal operation and system disturbance. The controller can respond to disturbances such as load increase, load loss, loss of some generating units and short circuit. The controller monitors the balance between the load and the generation in the system. This task can be performed by monitoring the system frequency; because the system frequency indicates a balance or imbalance of the power generated and the load .Under normal operating conditions, the difference between the load and the generation is zero, in this case the system frequency will be at nominal value 50Hz. On the other hand when the load is more than the active power generated the system frequency will be under 50Hz. If the system frequency reaches value below 50Hz the under frequency protection will operate to trip the generators. Also when the active power generated exceeds the load for value of more than 50Hz the over frequency protection will operate to trip the generators. According to G59/1 recommendation the protection settings for under frequency is 49.5 Hz and 50.5Hz for over frequency to trip the generator [17]. Either under frequency or over frequency will lead to system blackout. To avoid this blackout the system frequency has to be prevented to reach the threshold values. Therefore frequency control is essential for secure and stable operation of a power system. This target has been achieved using the control technique proposed in this work.

2. LOAD-FREQUENCY CONTROLLER DESIGN

A typical arrangement of the proposed controller is shown in Figure 1 .The load-frequency controller consists of measurement units, calculation units and logic unit. This made the difference from conventional automatic generation control, which has no control logic. The controller is mainly a set of mathematical instruction used to control and check the system operating condition. In this work the rate of change of frequency (ROCOF, df/dt) has been used to calculate the change in the active power demand in the system. Also the frequency error has been used to check the system operating condition and decide whether to increase or decrease the output power from PV units, if the system frequency deviation occurs.

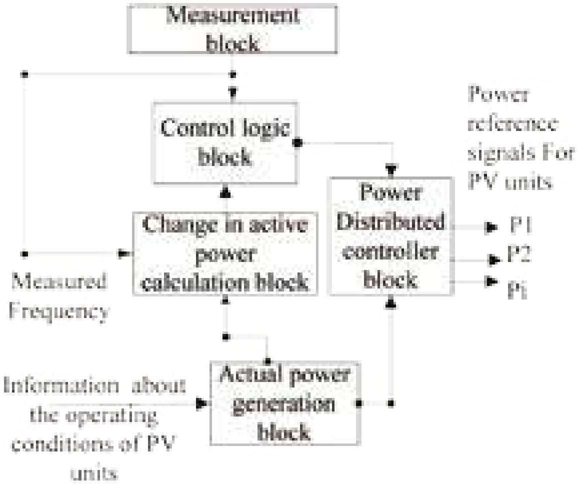

Figure 1: A block diagram of the load-frequency control system

2.1 The algorithm of the load-frequency controller

Figure 2 shows the flowchart of the load-frequency controller.The function of the control logic of the load-frequency controller is to detect whether there is disturbance or not and if there is disturbance its type has to be defined; under frequency or over frequency, then send appropriate control signal to the PV units to increase or decrease their outputs according to the type of disturbance.

The algorithm of the controller starts with:

1. Start after system initialization completes
2. Measure the system frequency
3. Measure the system power generation.
4. Calculate the frequency error,

$$f_{error} = f_{set} - f_{meas} \quad (1)$$

5. Record the actual set points for every PV unit from the local controllers $(P_{i\text{-}ac})$ in [MW].
6. Calculate the total rated power of all PV units (P_{Tpv}) in MW

$$P_{TPV} = \sum_{i=1}^{i=n} P_{i-rat} \quad [MW] \qquad (2)$$

P_{i-rat} = rated power of PV unit (i) in [MW]

7. Calculate the average value of total actual generation of PV units P_{av}.

$$P_{av} = \sum_{i=1}^{i=n} P_{i-par} \qquad [pu]\ (3)$$

Where P_{i-par} is the actual participation of PV unit i based on the total rated power of all PV units.

$$P_{i-par} = \frac{P_{i-ac}}{P_{TPV}} \qquad [pu] \quad (4)$$

8. Calculate the power(P_{dif}) that can be provided by PV units when under frequency occurs in MW. ($P_{dif} = P_{TPV} - P_{av}$). (5)
9. Calculate the power(P_{ovr}), that can be reduced from the PV units when over frequency occurs in MW.

$$P_{ovr} = \left[0.5 - P_{av}\right] \times P_{TPV} \ .(6)$$

10. Calculate the $\frac{\Delta f}{\Delta t}$ (ROCOF).
11. Calculate the change in the reference power setting for all PV units ΔP_{ref}:

$$(\Delta P_{ref} = -K \ \frac{\Delta f}{\Delta t}). \qquad (7)$$

12. If the frequency error equal to zero (f_{error} =zero) go to the next step, otherwise go to step16
13. The ΔP_{ref}=zero, the PV units power set points are actual set points.
14. Go to step20
15. If the frequency error is more than zero f_{error} >zero go to the next step, otherwise go to step18
16. The system frequency under rated value, the ΔP_{ref}= (under frequency value), ($0 \le \Delta P_{ref} \le P_{dif}$)..
17. Go to step20
18. If the frequency error is more than zero f_{error} <zero go to the next step, otherwise go to step2
19. The system frequency is over rated value, the ΔP_{ref}=(over frequency value), ($P_{OVF} \le \Delta P_{ref} \le 0$).

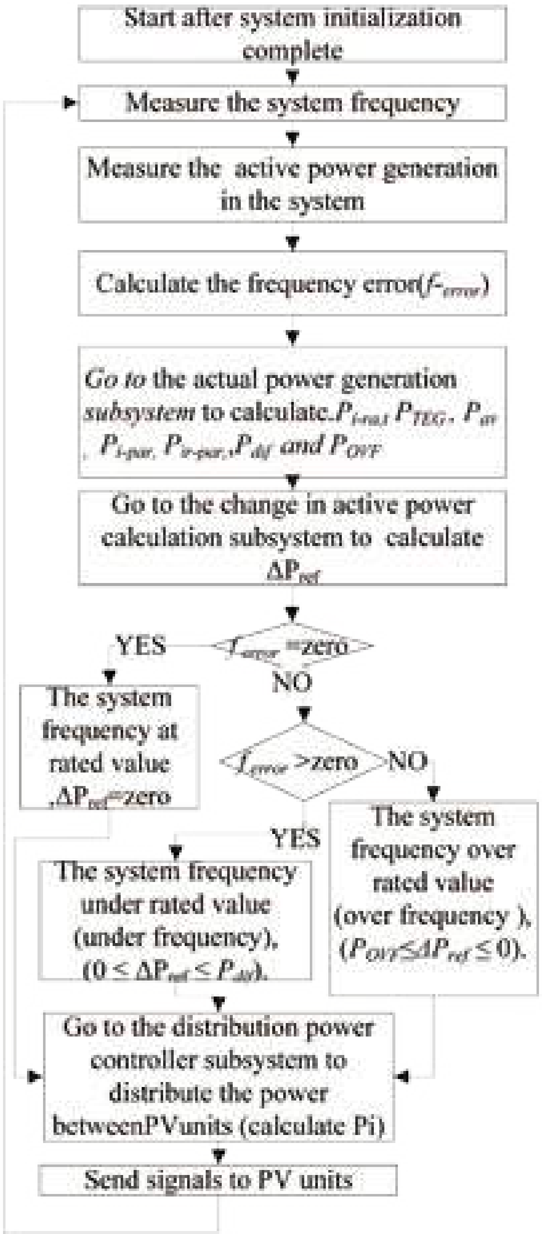

Figure 2: The flowchart of the load-frequency controller.

20. Go to the distribution power controller block to distribute the power between PV units
21. Send signals to PV units
22. Go to step2

Where: f_{error} is the frequency error,

P_{i-ac} is the actual set points for every PV units in [MW].

P_{Tpv} is the total rated power of all PV unit in MW.

$P_{i\text{-}rat}$ is the rated power of PV unit (i) in [MW].

P_{av} is the average value of total actual generation of PV units

P_{i-par} is the actual participation of PV unit i based on the total rated power of all PV units.

P_{dif} is the power that can be provided by PV units when under frequency occurs in MW.

P_{OVF} is the power that can be reduced from the PV units when over frequency occurs in MW.

$\frac{df}{dt}$: is the rate of change of frequency [Hz/s].

ΔP_{ref} is the change in the reference power setting for all PV units.

3. SYSTEM WITH PV UNITS WITH LOAD-FREQUENCY CONTROL

The load-frequency controller has been successfully implemented and tested using PSCAD/EMTDC. Figure 3 shows the EHV1 33kV rural network model [18] used to evaluate the performance of the general control approach that is proposed in this work. It includes three synchronous generators (G1, G2 and G3) have similar rating represent the main system providing 34.2MW connected to 132KV bus (bus 100) and one interconnected generator which provides 4MW to the network is connected o 33KV bus at bus 336 Also the network has long lines, including a sub-sea cable between buses 318 and 304.The total load is 38.16MW and 7.74 MVAr. As shown in the network the PV technology used in this study is Photovoltaic (PV) with 26.2% penetration (10 MW) for 9090 customer s (1.1 kW per customer). Represented by five Photovoltaic (PV) units the rate of every unit is 2MW (1818 customer). These units are connected at different locations to the EHV1 33kV rural network (1101, 1106, 1108, 1114 and1115).

The actual output power of Photovoltaic (PV) units is as follows; 1.6 MW (80%) for the units connected to bus 1101, 1.5 MW (75%) for the units connected to bus 1108, 1.46 MW (73%) for the units connected to bus 1106, 1.4 MW (70%) for the units connected to bus 1115, and 1.34 MW (67%) for the units connected to bus 1114.

3.1. Photovoltaic (PV) model

PV system consists of a PV generator, maximum power point tracker (MPPT), energy storage (for example a battery), and a power conditioning system [19-23]. A PV generator can contain several PV arrays; each array is composed of several modules and each module is composed of several solar cells. Photovoltaic (PV) units with help of solar cells convert the sun light directly into electrical energy. The MPPT is used to ensure that the PV array generates the maximum power for all irradiance and temperature values. The battery bank stores energy when the power supplied by the PV modules exceeds load demand and releases it back when the PV supply is insufficient. The power conditioning system contains a DC to DC converter and DC/AC inverter, isolation transformer and filter. Its function provides an interface between all the elements of a PV system and the grid. It is also used to give protection and control to the system [1]. Figure 4 shows schematic diagram of PV.

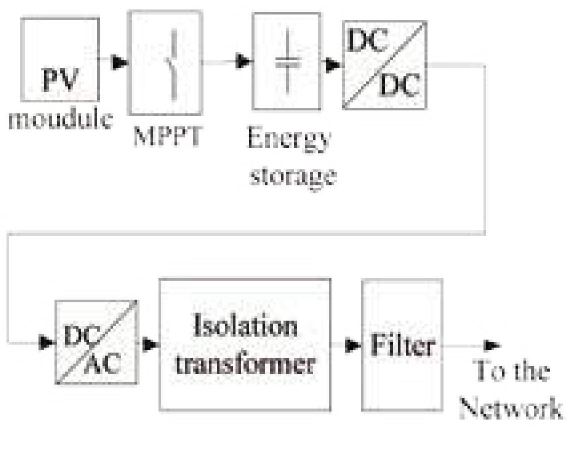

Figure 3: PV schematic diagram

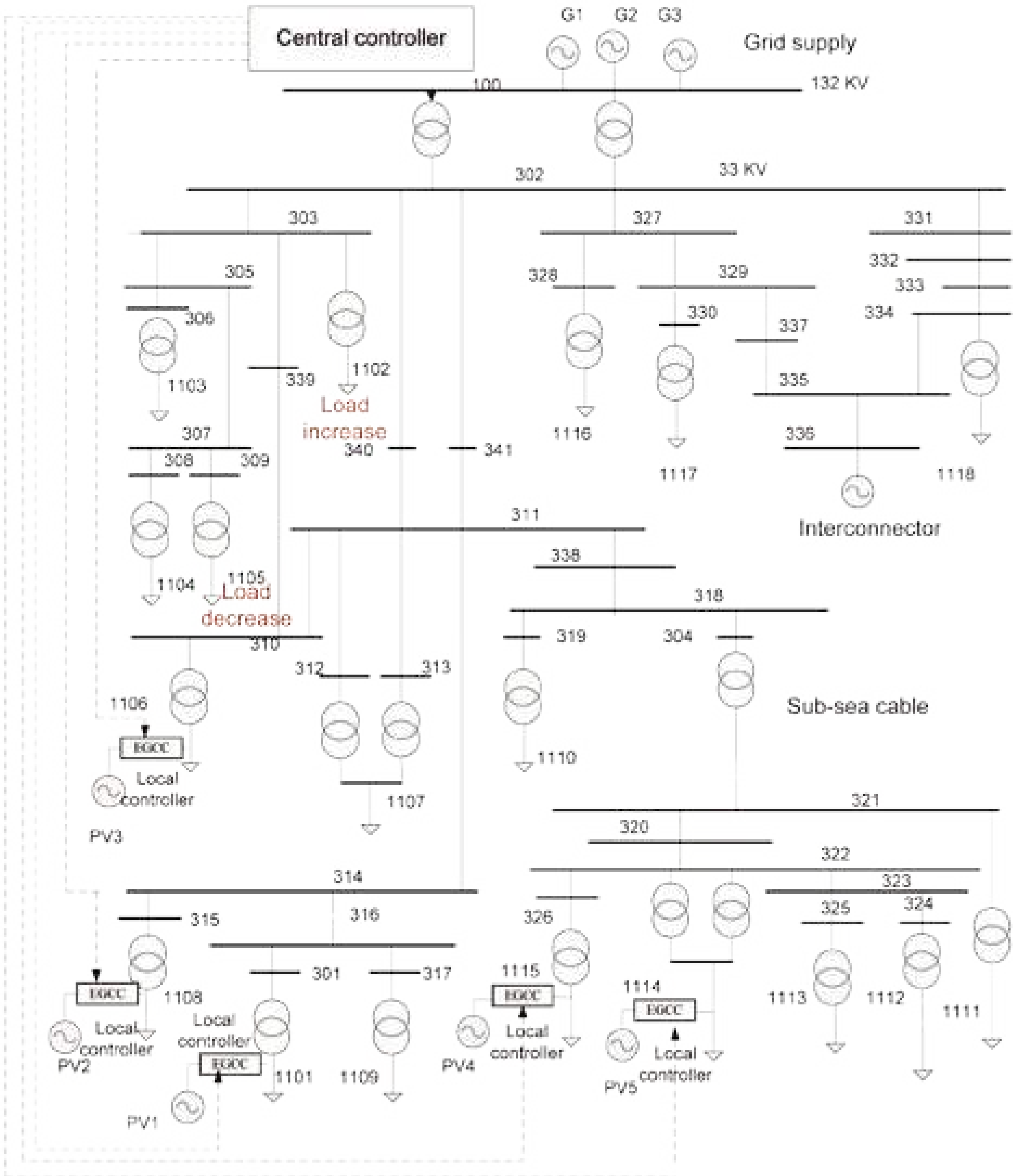

Figure 4: Network with Photovoltaic (PV) units used in the analysis

4. CASE STUDY

In order to investigate participation of Photovoltaic (PV) units in frequency control and test the performance of proposed controller, the two types of system disturbances load increase and load loss have been considered. These types of testing are applied on the EHV1 33kV rural network with 22.6% penetration of Photovoltaic (PV) .The strategy consists of increasing or decreasing their production to compensate the difference between the generation and the load to prevent the system frequency from reaching value beyond this limit (49.5-50.5 Hz). This will be achieved by the central controller that sends signals to Photovoltaic (PV) units to change their outputs according to the type of disturbance to restore the system frequency to the normal operating limits.

4.1 Under frequency test (load increase)

In order to investigate the system frequency behaviour with photovoltaic units with load-frequency control, the disturbance considered is increasing in load. The duration of the simulation is 70s during the test. At the beginning the balance between consumption and generation is ensured and maintained, then suddenly at t= 10s, load " load 1102" is increased by 3.816MW (10% from the total load). As shown in Figure 5 the output power from main system increased to supply the change in the load that leads to decreasing in the system frequency as shown in Figure 6 due to imbalance between electrical and mechanical torque of the main generators as clearly observed in Figure 7 (G1 as an example).Once the disturbance is detected by the central controller, the central controller sends signals to PV units to increase their output power as shown in Figure 7 and Figure 8 (out put power from PV unit1 as an example). The total output power from PV units increased to maximum value during first 3sec after disturbance. This increase of output power from PV units is achieved by the local control system of the units, as shown in Figure 9 (load angle of the PV unit1 as an example). The control system increases the power angle of the inverter to change the output power from every PV unit. Also as shown in Figure 8 the change in the system frequency has no impact on the performance of the photovoltaic units due to inertia less of the units .At t=20s, generators G1, G2 and G3 start to increase output power, at the meantime the PV units start to reduce their out put power until reaching the actual operating condition before the disturbance at t= 20s. As shown in Figure 6 the frequency of the system is 49.565Hz which is within the limits of normal operation .Also Figure 6 shows using the proposed controller there are no oscillations in the system frequency before restoration to its initial condition.

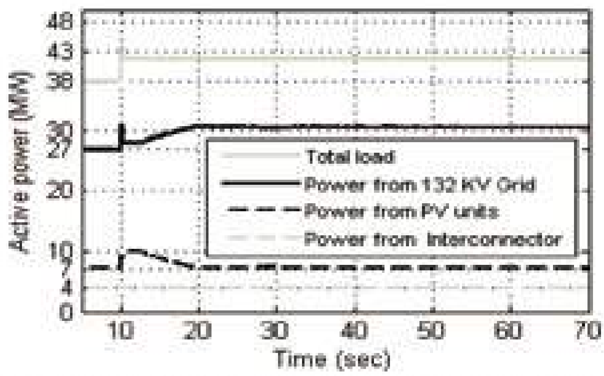

Figure 5: Active power generation in the system

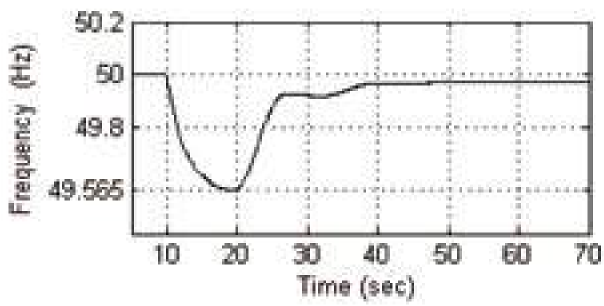

Figure 6: system frequency behaviour with of PVs with load-frequency control

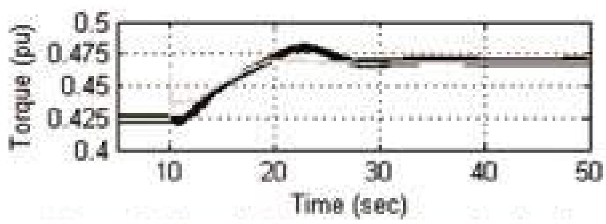

Figure 7: Electrical torque and mechanical torque for synchronous generators

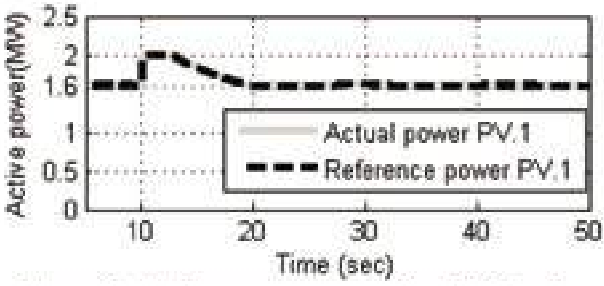

Figure 8: Active power output for all PV units

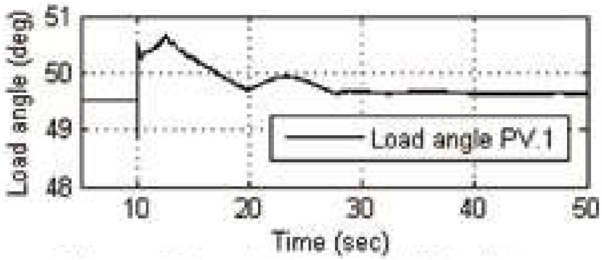

Figure 9: Load angle for all PV units.

4.2 Over frequency test (load decrease)

In order to investigate the system frequency behaviour with photovoltaic units with load-frequency control, the disturbance considered is decreasing in load. The duration of the simulation is 70s during the test. At the beginning the balance between consumption and generation is ensured and maintained, then suddenly at t= 10s, load "load 1105" is disconnected (10% from the total load). As shown in Figure 10 the output power from the main system decreased to compensate the difference between the load and generation .The change in the load that leads to increasing in the system frequency as shown in Figure 11 is due to imbalance between electrical and mechanical torque of the main generators as shown in Figure 12 (G1 as an example). Once the disturbance is detected by the central controller, the central controller sends signals to PV units to decrease their output power as shown in Figure 10 and Figure 13 (output power from PV unit1 as an example). The total output power from PV units decreased to half total rated value during first 3sec after disturbance. This decrease in output power from PV units is achieved by the local control system of the units, as shown in Figure 14 (load angle of the PV unit1 as an example). The control system decreases the power angle of the voltage of the inverter to change the output power from every PV unit. At t=15s, generators G1, G2 and G3 start to decrease output power while the PV units start to return to the actual operating condition before the disturbance at t= 18s.As shown in Figure 10 the frequency of the system is 50.366Hz which is within the limits of normal operation .Moreover by using the proposed controller there are no oscillations in the system frequency before restoration to its initial condition.

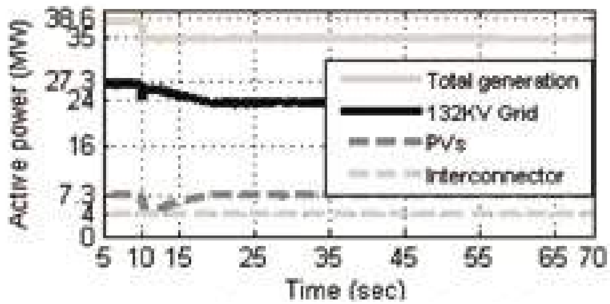

Figure 10: Active power generation in the system

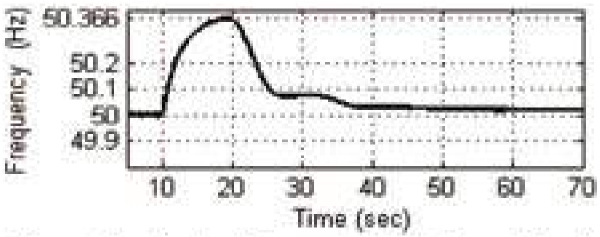

Figure 11: System frequency behaviour with of PV with load-frequency control

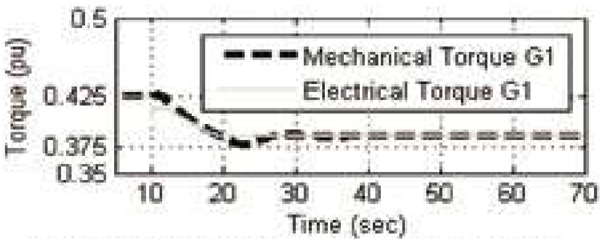

Figure 12: Electrical torque and mechanical torque for synchronous generators

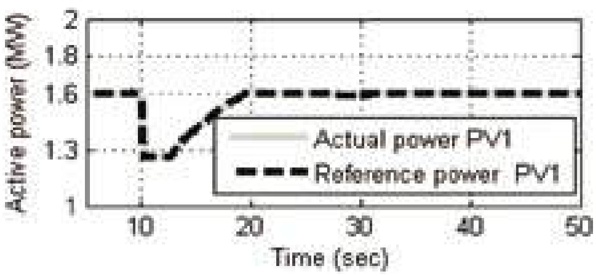

Figure 13: Active power output for all PV units

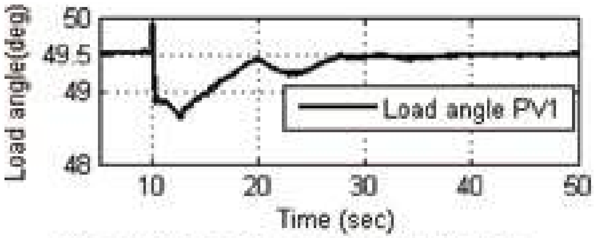

Figure 14: Load angle for all PV units.

5. COMPARISON OF SYSTEM FREQUENCY RESPONSE DURING DIFFERENT OPERATING CONDITIONS

In order to compare the system frequency behaviour with no participation of photovoltaic units without load-frequency control and with photovoltaic units with load-frequency control, the system frequency response of three cases are plotted together. The two types of tests were done under frequency and over frequency tests as described in the following subsections.

5.1. Under frequency Test (load increase)

The aim of this test is to investigate the response of the controller when an additional load (3.816MW) is connected to a low-voltage network (at t=10sec) and to compare the system frequency behaviour with no participation of photovoltaic units and with photovoltaic units without load-frequency control. Figure 15 illustrates the system frequency with participation of PV with and without load-frequency control. The results are compared with each other and with the base case, where there is no photovoltaic unit connection in the system. The results illustrated that in a case of the system without photovoltaic units when a new load is connected the frequency of the system decreases to value 48.8Hz, the threshold value (49.5Hz). This energizes the under frequency protection which in turn leads to a blackout in the system. Using photovoltaic units without load and frequency control the frequency is 48.93Hz that leads to these consequences. At frequency of 48.93 the system performed better than at 48.8 Hz but still led to a blackout. However, the study showed that by connecting the photovoltaic (PV) to the system with load and frequency controller excellent response during steady state and disturbance was demonstrated. As shown in the figure the frequency of the system is 49.565Hz which is within the limits of normal operation .Moreover by the proposed controller there are no oscillations in the system frequency before restoration to its initial condition.

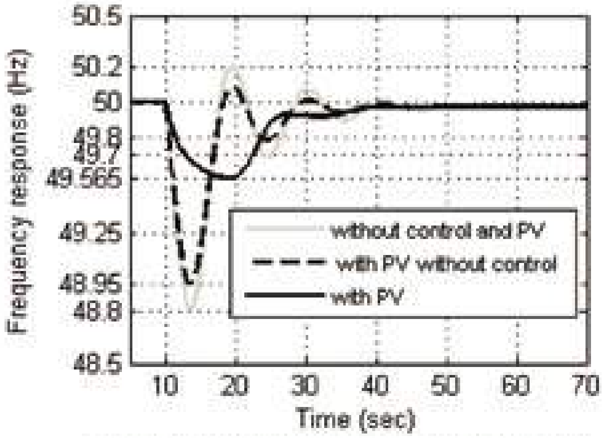

Figure 15: System frequency behaviour (load increase)

5.2. Over frequency test (load decrease)

The aim of this test is to investigate the response of the controller when a load "load 1105" (3.1MW) is disconnected from the low-voltage network (at t=10sec) and to compare the system frequency behaviour with no participation of photovoltaic units and with photovoltaic units without load-frequency control. Figure 16 illustrates the system frequency with participation of photovoltaic units with and without load-frequency control. The results are compared with each other and with the base case, where there is no photovoltaic unit connection in the system. The results illustrated that in a case of the system without photovoltaic units when a load is disconnected the frequency of the system increases to value 50.9Hz, the threshold value (50.5Hz). This energizes the over frequency protection which in turn leads to a blackout in the system. Using photovoltaic units without load and frequency control the frequency is 50.84Hz which leads to these consequences. At frequency of 50.84Hz the system performed better than at 50.9Hz but still led to a blackout. However, the study showed that by the connecting the photovoltaic (PV) to the system with load and frequency controller excellent response during steady state and disturbance was demonstrated. As shown in the figure the frequency of the system is 50.366Hz which is within the limits of normal operation .Moreover by using the proposed controller there are no oscillations in the system frequency before restoration to its initial condition.

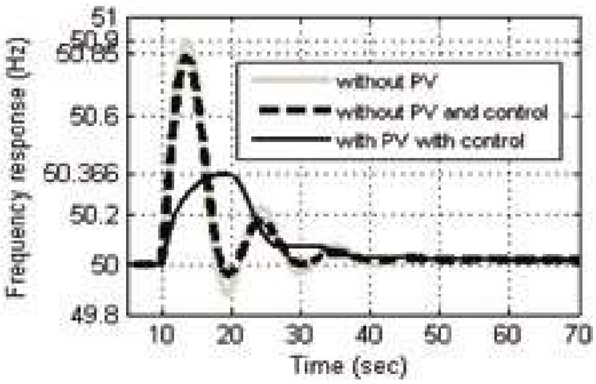

Figure 16: System frequency behaviour (load decrease)

6. CONCLUSION

The load-frequency controller has been successfully implemented and tested using PSCAD/EMTDC. A real distribution system with a load scenario is used in the test. This study shows that large penetration of PVs connected near the load area with load and frequency control has a significant impact on the stability of the system. Moreover by using the proposed controller there are no oscillations in the system frequency before restoration to its initial condition. In addition the results show that it is necessary to coordinate between the central controller and the local controllers of PV units in order to maintain the system frequency within limits.

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