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Efficient Transient Stability and Frequency Response in Solar Photovoltaic Generation

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Abstract: *The technology to produce electricity in a renewable manner is to apply solar cells to exchange the energy emitted by the solar irradiance into electricity. Photovoltaic (PV) energy production is the modern subject of much commercial and academic interest and its associated operating behavior and associated voltage and frequency control are improved. Unlike conventional power production, photovoltaic generators have no rotating parts, have thus no inertia and changes in output voltage can appear extremely rapidly. This potentially causes a problem for the installation when the output energy of the photovoltaic production varies rapidly due to the irradiance changes caused by random movement of the cloud cover over the clear sky. As the cloud shadows pass over a photovoltaic (PV) array, the PV output voltage decreases. Voltage control techniques that might help overcome the voltage fluctuation problems caused by changes in irradiance due to moving clouds have been simulated. Simulation results obtained from these voltage control methods show that when the PV generator is operating at a constant lagging power factor, it can mitigate the voltage fluctuation problem effectively. Simulation results acquired from proposed transient stability and voltage control techniques present that when the PV generator is operating at a constant lagging power factor, it can mitigate the voltage fluctuation problem effectively. Transient stability and voltage control from the PV inverter itself has better performance in helping mitigate the voltage fluctuation problem.*

Keywords: *Solar Photovoltaic, Transient Stability, Frequency Response, Voltage Stability, Voltage Control.*

I Introduction

Solar energy is one of the most practical renewable energy sources in the Earth. The output power of photovoltaic (PV) system is affected by the incident solar irradiation and the ambient temperature [1]. Photovoltaic (PV) systems convert light energy into electricity. The term photo is from the Greek which mean "light". "Volt" is named for Alessandro Volta (1745-1827), a pioneer in the study of electricity. Photovoltaic (PV) is then could literally mean "light-electricity" [2]. A grid connected PV system converts sunlight directly into ac electricity [3, 4]. Recent work on solar photovoltaic system shows that in the medium to longer term PV generation may become commercially so attractive that there will be large-scale implementation in many parts of the developed world [5]. The main purpose of the system is to reduce the electrical energy imported from the electric utility. It shows a functional diagram of the basic configuration of a grid-connected PV system. Figure 1 shows a functional diagram of the basic configuration of a grid-connected PV system. The DC output current of the PV array I_{pv} is converted into ac and injected into the grid through an inverter [6]. The controller of this inverter implements all the main control and protection functions:- Maximum Power Point Tracking (MPPT), protection relay and detection of islanding operation [7–10].

I-A Solar Irradiance

Solar irradiance is the radiant power incident per unit area upon a surface. It is usually expressed in W/m^2. . Radiant power is the rate of flow of electromagnetic energy[11]. Sunlight consists of electromagnetic waves composed of photons at different energies, which travel at constant speed. Solar radiation has a wave like characteristic with the wavelength (λ) inversely proportional to the photon energy (E).

$$\lambda = \frac{hc}{E} \tag{1}$$

where, c = velocity of light
h = planck's constant

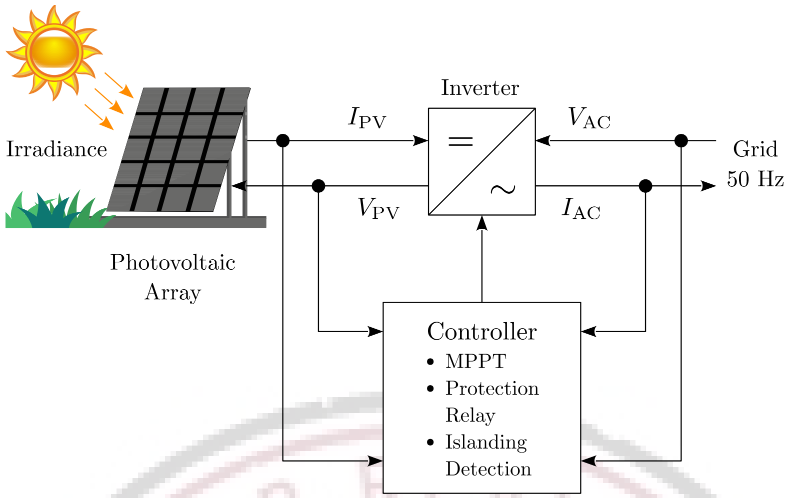

Figure 1: Basic Configuration of Grid Connected PV Generation

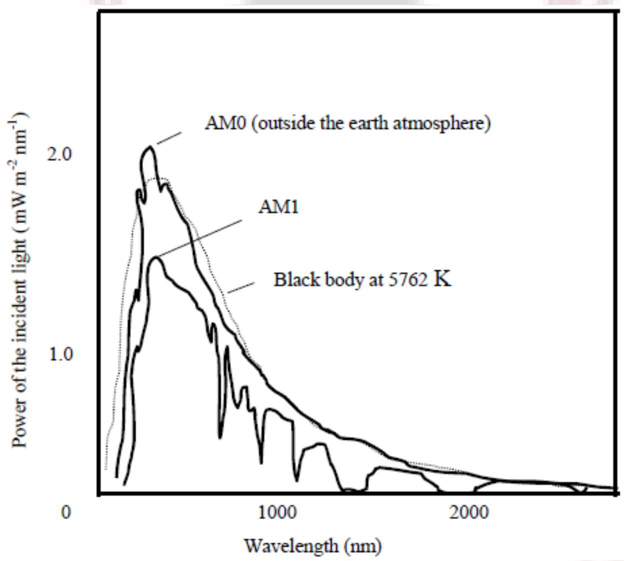

Figure 2: Solar Spectrum

The spectrum of the sunlight is shown in Figure 2. The light from the sun has a spectrum close to the light from a black body at a temperature of 5762 K. The dotted line shows black body radiation at this temperature. This is in good agreement with the AM0 curve which shows the spectrum outside the earth's atmosphere on a plane perpendicular to the sun at the mean earth-sun distance. The power density outside the earth's atmosphere is 1367 W/m^2. and this is known as the solar constant. Air mass refers to the relative path length of the direct solar beam through the atmosphere. The path of the light through the atmosphere is shortest when the sun is at its zenith (perpendicular to the earth's surface), the path length is 1.0 (AM 1.0) and this gives rise to the AM1 spectrum. Obviously, the sun is not always at the zenith. When the angle of the sun from zenith increases, the air mass increases so that at an angle of 48.2° the air mass is 1.5 and at an angle of 60° the air mass is 2.0 as presented in Figure 3. AM 1.5 has been adopted as the standard sunlight spectrum for terrestrial arrays [12–16].

Usually, the peak power output of a PV inverter is measured under AM1.5 (1kW/m^2). sunlight with a junction temperature of 25° C. This is the so-called standard test condition (STC) [17].

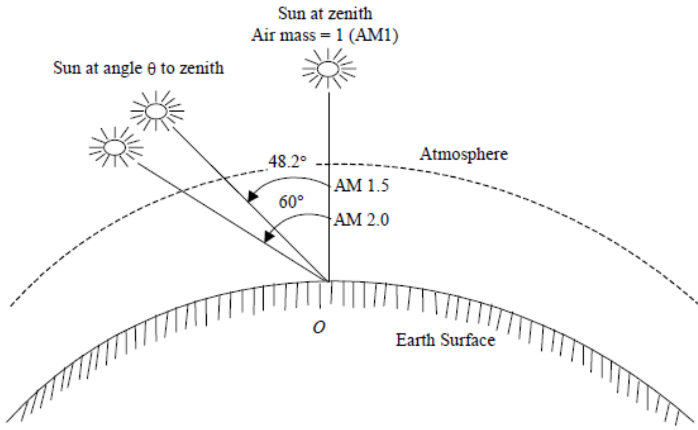

Figure 3: Air Mass Concept

II Related Work

Munkhchuluun *et al.* [18] investigated the impact of large-scale solar-PV generation on long-term voltage stability. A rigorous theoretical analysis was performed with a simple test system to compare the long-term voltage stability (LTVS) impact of the solar-PV generation with the SG. Then the Nordic test system was used to conduct a system wide long-term voltage stability (LTVS) study with solar-PV generation. The dynamic QV curves were used to demonstrate how power system approaches its voltage instability point during the long-term voltage stability (LTVS) phenomenon. The solar-PV system performance for long-term voltage stability (LTVS) is compared with the synchronous generator (SG), and key influential parameters of the solar-PV system affecting voltage stability was analysed.

Simulation results show that when the solar-PV system has a 10% oversized inverter with an improved reactive power gain, it performs better than the stressed synchronous generator (SG) for long-term voltage stability (LTVS) as the solar-PV systems can provide enhanced reactive power support compared to SGs. However, depending on the relative loading level of replaced synchronous generator (SG) which activate their over excitation limiter (OEL), the large-scale solar-PV systems have both beneficial and adverse impact on stressed power systems. Moreover, it was observed that reactive power prioritization (without any reactive current limits) is not effective for long-term voltage stability (LTVS), as it will lead to voltage collapse due to significant active power reduction in the power network. Furthermore, this study has also shown that variation of solar-irradiance and temperature could have some adverse impact on long-term voltage stability (LTVS), in particular when solar-irradiance decreases and ambient temperature increases.

Darussalam *et al.* [19] analyzed the effect of fluctuative photovoltaic generation on system frequency and determined the maximum level of photovoltaic penetration integrated to a 20 kV distribution grid which is in accordance with Indonesian grid code. A MATLAB Simulink is used to simulate the solar photovoltaic integrated into the distribution grid which the photovoltaic penetration are varied to be 25%, 20%, 15% and 10% of peak load.

They presented response frequency on a 20 kV distribution grid to serve a load of 1000 kW with frequency system on 50 Hz. A MATLAB Simulink is used to simulate the integrated of solar PV generation to the 20 kV distribution grid 20. The load is supplied by Distributed Generation consist of 3 sources including 20 kV Distribution grid with power capacity of 850 kW, Solar PV plant with power capacity of 250 kW.

Hoke *et al.* [20] introduced the rapid active power control method which has been experimentally shown to provide very fast and accurate response to a demanding range of grid frequency events. The experimental validation used two real PV arrays to demonstrate that the method is robust to realistic changes in weather conditions. Used in conjunction with a PV maximum power point estimation method experimentally validated here, the RAPC method enables a suite of fast-responding PV inverter active power control methods, including but not limited to the fast power-frequency droop response demonstrated here.

III Proposed Method

As the concern over global warming increases, renewable energy source become a more significant source of energy. Among these renewable energy sources, PV generation is attracting a growing amount of domestic and commercial interest. A large penetration of PV generation would have far reaching consequences not only on the distribution network but also on the transmission grid and the rest of the generators. The effect of a large penetration of PV generation on the stability and security of the power system must therefore be considered carefully. In particular, the response of PV generators to disturbances can aggravate these incidents. This section presents proposed transient stability analysis and frequency response of PV generation.

III-A Proposed Frequency Response Model to the Rapid Changes in Solar Irradiance

The connection of a large amount of Photovoltaic (PV) generation to the grid could have far reaching consequences not only on the distribution networks but also on the transmission grid and the rest of the generators. The most severe disturbance in the output of PV generation will probably be encountered when a band of clouds sweeps over an area with a large concentration of PV generators. This could result in a fairly large and sudden variation in the PV output. The condition would be aggravated if this change in irradiance occurred during a period of rapid increase in load.

III-A.1 Model for Uniform Solar Irradiance Distribution

In this case the Photovoltaic (PV) generating units within the plant are assumed to have the same operating points. When reducing the aggregate model of the large PV plant, the following assumptions are made:

- The Mega Volt-Amp (MVA) rating of the large PV plant equivalent, $S_{\Sigma,\Sigma,}$ is the sum of the MVA ratings of the PV generating units:

$$S_{\Sigma,\Sigma} = \sum_{i=1}^{Y}\sum_{j=1}^{N} S_{i,j} \tag{2}$$

  where $S_{i,j}$ is the Mega Volt-Amp (MVA) rating of the PV generating unit j being in the column i.

- The equivalent PV generating plant supplies the same amount of electric power to the grid:

$$P_{\Sigma,\Sigma} = \sum_{i=1}^{Y}\sum_{j=1}^{N} S_{i,j} \tag{3}$$

  where $P_{i,j}$ is the electric power supplied by the PV generating unit j being in the column i and $P_{\Sigma,\Sigma}$ is the electric power supplied by the whole PV plant.

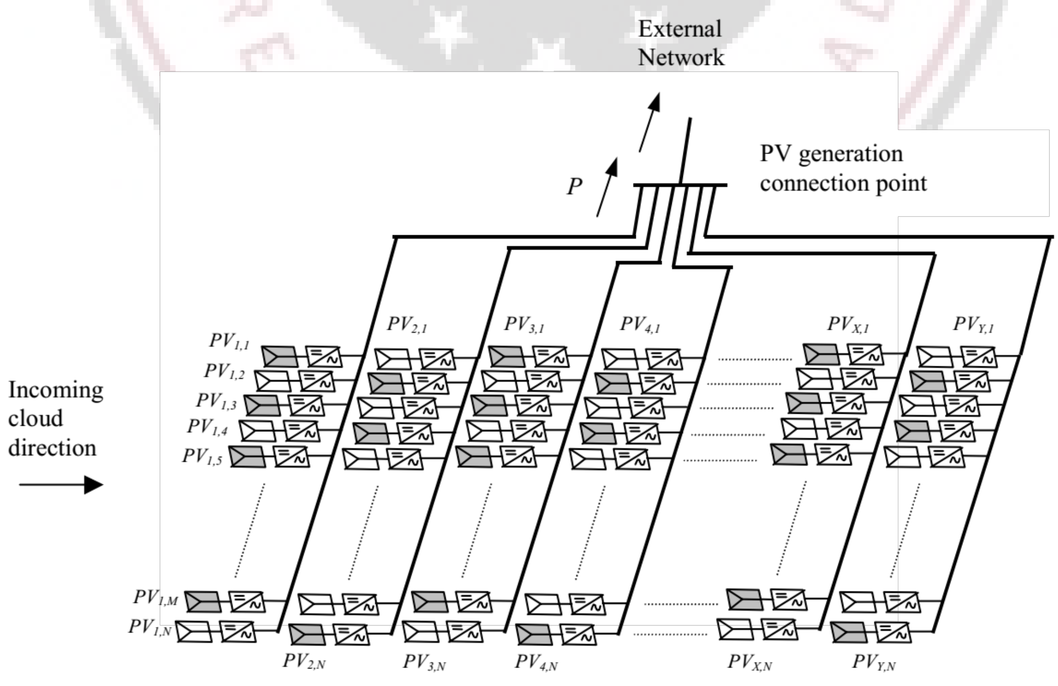

Figure 4: The Aggregate Model of Large Photovoltaic (PV) Plant Connected to the Power Grid

Equation 2 and III-A.1 imply that the equivalent PV plant can be defined by a simple addition of the Mega Volt-Amp (MVA) ratings and an addition of the electric power output of the individual generating units. The incoming cloud shown in Figure 4 is assumed to cover all the individual PV generating units in the equivalent plant at the same time. Figure 5 represents this one-PV generator equivalent.

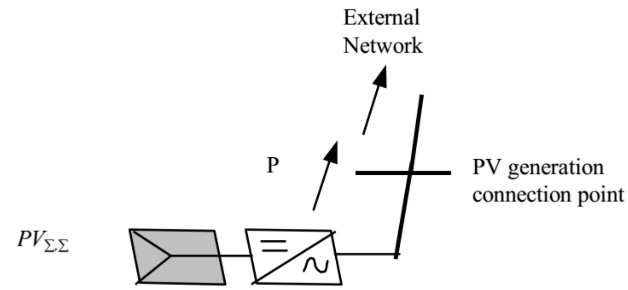

Figure 5: One-PV Generator Equivalent

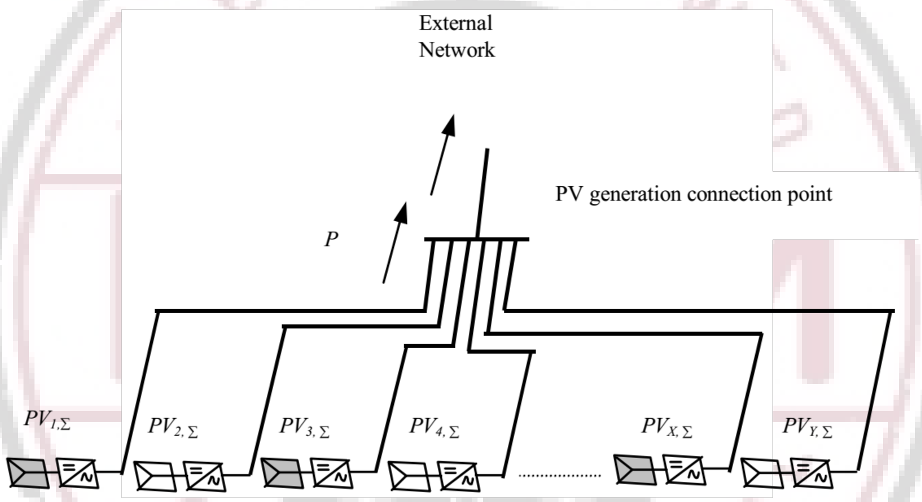

Figure 6: Multi-PV Generator Equivalent

III-A.2 Model for Non-uniform Solar Irradiance Distribution

In this case the incoming cloud is such that:

- Its direction is as presented in Figure 6.
- The cloud takes k seconds time to move from the first column to the second column of the PV generating units. In other words, the irradiance is shifted by k seconds for each column of PV generating units.

Since the operating points of the PV units in each column are identical, the outputs of the PV units in each column are added and a multi-machine equivalent comprising of Y PV generating units is obtained. This multi-generators equivalent is shown in Figure 6. The Mega Volt-Amp (MVA) ratings, $S_{\Sigma\Sigma}$ the electric powers, $P_{\Sigma\Sigma}$ of the equivalent PV plants are given by:

$$S_{\Sigma\Sigma} = \sum_{i=1}^{Y} S_{i,\Sigma} \tag{4}$$

$$P_{\Sigma\Sigma} = \sum_{i=1}^{Y} P_{i,\Sigma} \tag{5}$$

The response of the system when subjected to sudden changes in irradiance caused by a passing cloud. Different amounts of PV penetrations are considered. The integration of the PV generation in the local area caused the most impact on the bus voltages in the system. The sampling rate of the irradiance data is 1 sample/second. Both uniform and non-uniform solar irradiance distribution are considered.

IV Result Analysis

The simulation result studies will present the effectiveness of the voltage control methods which describe mitigating the voltage fluctuation problems that arise when sudden change in irradiance affect photovoltaic (PV) generation. The voltage control methods are simulated in the system assuming the PV generators are connected at bus and the simulation studies were performed for minimum and maximum PV penetration over a 60 seconds period on a typical partly cloudy day.

IV-A Simulation Result (PV Penetration without Transient Stability and Voltage Control)

Figure 7 presents the simulation result for the case of photovoltaic (PV) generation without any transient stability and voltage control. The PV generator is operating at unity power factor. The reactive power generated is zero as shown in

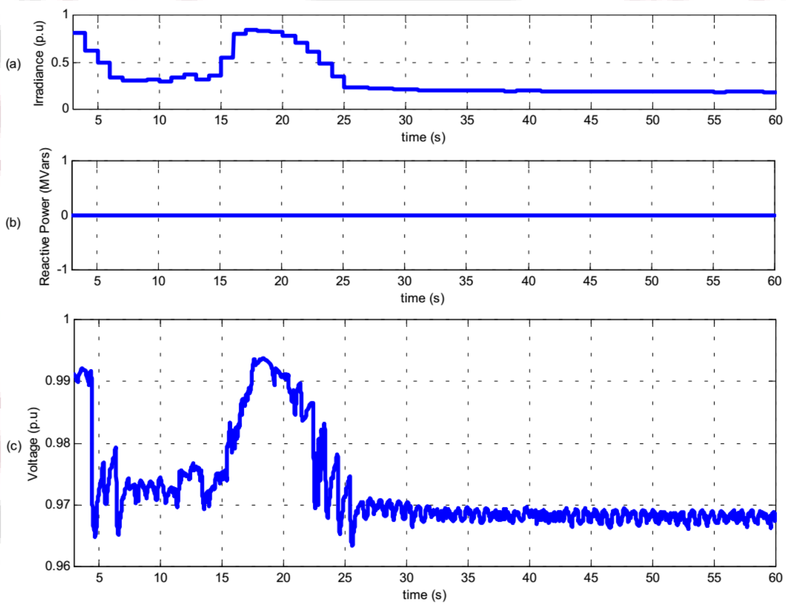

Figure 7: Photovoltaic (PV) Penetration without Transient Stability and Voltage Control

Figure 7. The bus voltage fluctuates when the irradiance (shown in Figure 7(a)) varies over a 60-seconds period. For the minimum PV penetration case, Figure 7(c), the bus voltage is near o 0.994 p.u. at $t = 18$ s when the irradiance value is at its maximum. At $t = 25$ s, the bus voltage is 0.968 p.u. The difference in bus voltage between the maximum and minimum irradiance is thus 0.026 p.u. For the case of maximum PV penetration, the difference in bus voltage between the maximum and minimum irradiance is even larger, i.e. 0.057 p.u.

The effect of operating the connected PV generators with constant power factor controller on the voltage profile of bus has been simulated. The simulation results show that when the PV generator is operating with a lagging power factor, they generate reactive power. When the irradiance is high, the active power is high and results in large amount of reactive power being generated. When the irradiance is low, the active power is low and results in a very small amount of reactive power being produced. This approach increases the bus voltage during periods of high irradiance but does not change much the behavior of the system during periods of low irradiance as compared to the case of PV generation without voltage control. The difference of bus voltage during the maximum and minimum irradiance therefore increases.

IV-B Simulation Result (PV Penetration using Transient Stability and Voltage Control)

Figure 8 presents the simulation results for the case of minimum and maximum PV penetration with transient stability and voltage control. In this case, the targeted reference voltage V_{ref} is set at 0.975 p.u. The bus voltage is well regulated

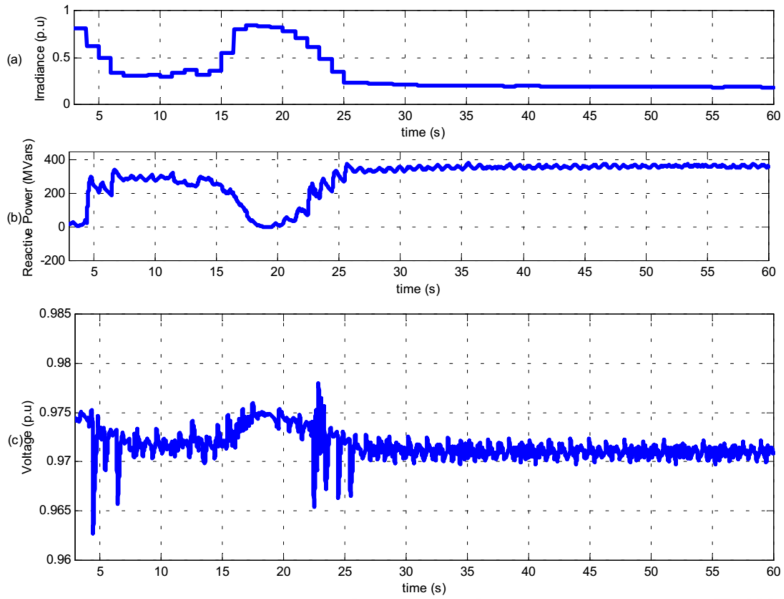

Figure 8: Photovoltaic (PV) Penetration using Transient Stability and Voltage Control

at the reference voltage at any irradiance value. However, this type of operation places a heavy demand on the transient stability and voltage control to supply or absorb reactive power from the network especially when the irradiance value is low. Therefore, the rating of the transient stability and voltage control used is very dependent on the amount of PV generation at the connected bus. The higher the PV generation is, the higher the rating of transient stability and voltage control is required and thus its associated cost will increase as well.

V Conclusion

The development of dynamic models of PV generation has been the object of only a few scientific works. A review of these research shows that the voltage reference signal from the photovoltaic system is assumed to be fluctuating at all times to the point corresponding to maximum power for the current irradiance level. The operation of the controller is not represented in several models. Simulation results obtained with proposed model suggests that PV generating units should respond to disturbances in irradiance and line voltage within milliseconds. Simulation results acquired from proposed transient stability and voltage control techniques present that when the PV generator is operating at a constant lagging power factor, it can mitigate the voltage fluctuation problem effectively. However, when the PV generator is operating in constant leading power factor, it helps to reduce the voltage fluctuation but the bus voltage will be kept at lower value. Transient stability and voltage control from the PV inverter itself has better performance in helping mitigate the voltage fluctuation problem.

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