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VOLTAGE AND FREQUENCY CONTROL FOR ISLANDED MICROGRIDS CONTAINING PHOTOVOLTAIC POWER PLANTS

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The article deals with the strategy of primary and secondary control for photovoltaic power plants in islanded microgrids. The first part describes the regulation possibilities of photovoltaic power plants and a characteristic of the virtual active and reactive power method. The following and final parts present the simulation model and results of primary and secondary control created in the MATLAB Simulink software environment. Inter alia, the aim of this article is also to assess the effect of load place on accurate power share achieving between two distributed generators.

K e y w o r d s: primary control, secondary control, microgrids, photovoltaic power plant, virtual powers method

1 INTRODUCTION

The main purpose of controlled distributed sources is the possibility of uninterruptible power supply to sensitive and important facilities thereby increasing the reliability and quality of power supplied in islanded microgrids [1]. In normal operation these microgrids are connected to the distribution networks and in the case of a grid fault occurrence they are disconnected.

Distributed generators working with renewable power sources such as photovoltaic and wind power plants should also be regulated sources. Thereby their negative impact is eliminated and the utilization of the energy potential of these primary sources is increased [2].

Since in the low voltage grids the resistance outweighs the reactance, the conventional frequency and voltage droop controls must be replaced with virtual control methods. The strategies of these methods are explained for example in [3,4,5].

In this paper, the active and reactive power method is applied in order to verify the primary frequency and voltage control. The virtual method is also used to create the secondary control circuit. Simulation results presented poor power sharing between two sources due to the mismatch in impedances of the distributed generation unit feeder. This may be eliminated by means of the inductive virtual output impedance control strategy that is described in [7].

2 REGULATION OF PHOTOVOLTAIC POWER PLANTS

In Fig. 1 one can see the basic scheme of a photovoltaic power system.

The photovoltaic power generators are connected to the grid generally by means of inverters with pulse-width modulation (PWM). These inverters are the sources of higher harmonics. To decrease their occurrence, LC filters are used which are placed between the inverter and the connection line to the Point of Common Coupling (PCC).

The photovoltaic power plants (PVP) are usually operated on the maximal power output and therefore we try

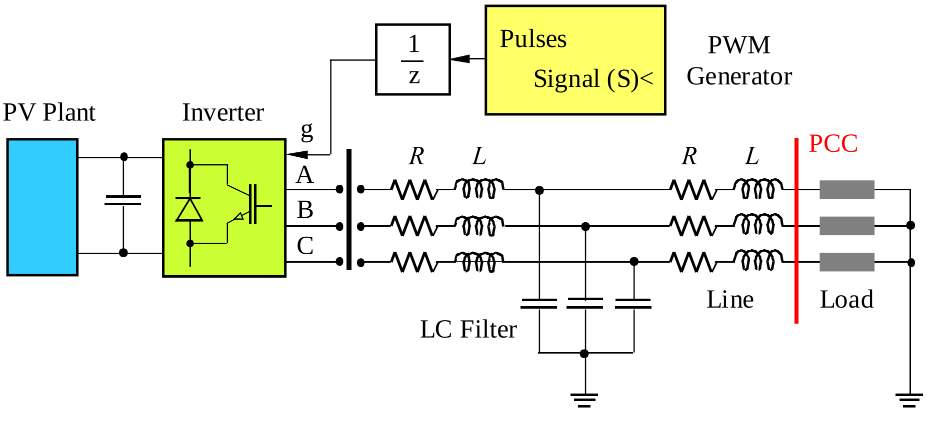

Fig. 1. Photovoltaic power system in microgrid

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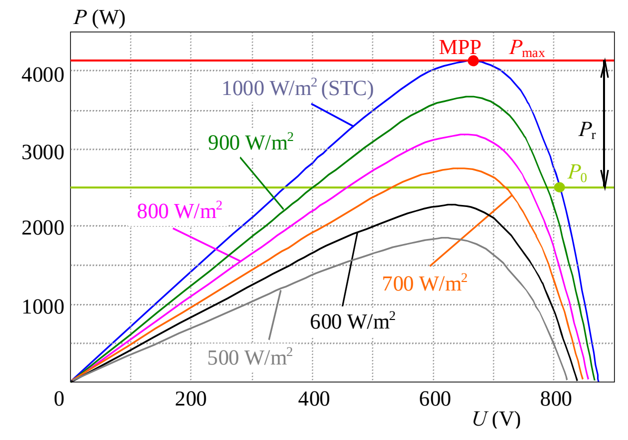

Fig. 2. Power margin

to find the Maximum Power Point (MPP) for operating them in atmospheric conditions at a given time. Nevertheless, then participation of these generators in voltage and frequency regulation is impossible. When it is necessary to make any power PV output deviation, the PV system is not able to increase or decrease its power output [8].

In this case other energy sources or storage devices are used to keep the balance between the supply and demand and frequency and voltage nominal values.

The PVP itself can participate in the frequency and voltage control, for example when they are operated at a point away from MPP shown in Fig. 2. On one hand this creates a power margin P_r enabling the regulatory process but on the other hand the amount and efficiency of electricity production drop [6].

3 CONTROL CIRCUIT FOR INVERTERS

The PV systems usually use three-phase voltage inverters which are composed of anti-parallel IGBT thyristors and diodes. Their control is fundamentally the same as the control of synchronous generators. Thereby the voltage and frequency values can be regulated by the static frequency and voltage characteristics as in the case of synchronous generators. These characteristic are derived from the transmitted real power between the source and load in the PCC.

Conventional voltage (Fig. 3) and frequency (Fig. 4) droop characteristics are applied in grids with dominant inductive behaviour ($R << X$), where $X = 2\pi f L$. In these parts of the network the frequency value depends on the active power balance and the voltage magnitude on the changing flow of reactive power.

In most cases the components of the distribution system impedance and reactance are negligible. The magnitudes of both the frequency and voltage are influenced by the active power as well as reactive powers. In the given part of the network the share of individual performance is determined by the impedance ratio (R/X) in the given part of network. Then, instead of traditional characteristics the so-called virtual methods are used [5]:

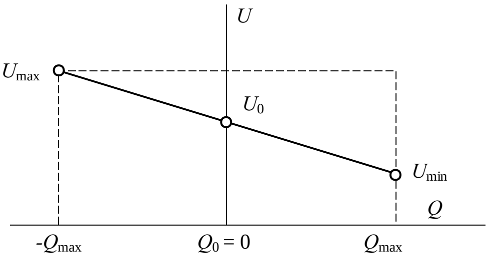

Fig. 3. Voltage droop characteristic in power systems with $R << X$

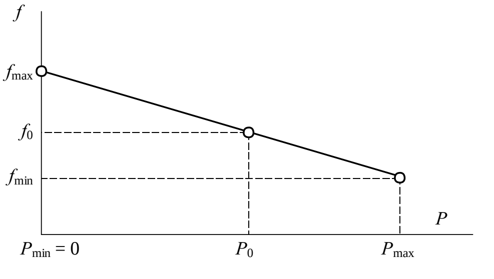

Fig. 4. Frequency droop characteristic in power systems with $R << X$

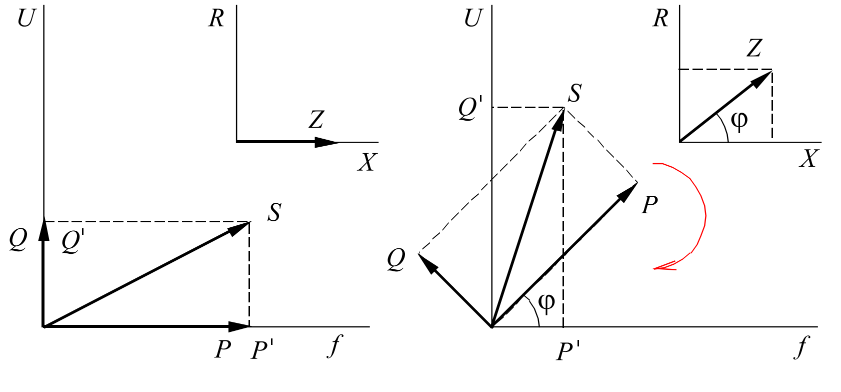

Fig. 5. Virtual powers method [2, 6]

- virtual active and reactive powers,
- virtual frequency and voltage,
- virtual impedance.

4 VIRTUAL ACTIVE AND REACTIVE POWERS METHOD

The method of virtual active and reactive powers is the easiest virtual method based on using the transformation matrix $\boldsymbol{T}$. This matrix turns the vectors of powers by angle φ so that their new positions correspond to their location in the situation, where $X >> R$. The transformed powers are called the virtual active power P' and reactive power Q'. The principle of this method is presented in Fig. 6.

$$\begin{bmatrix} P' \\ Q' \end{bmatrix} = \boldsymbol{T} \cdot \begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} \cos\varphi & -\sin\varphi \\ \sin\varphi & \cos\varphi \end{bmatrix} \cdot \begin{bmatrix} P \\ Q \end{bmatrix} \tag{1}$$

Assuming a small power angle leads to the static frequency $P' = f(f)$ and voltage $Q' = f(U)$ drop characteristics which are defined by the following relationships

$$\begin{gathered} f - f_0 = -k_p(P' - P'_0) = \\ -k_p \frac{X}{Z}(P - P_0) + k_p \frac{R}{Z}(Q - Q_0) \end{gathered} \tag{2}$$

$$\begin{gathered} U - U_0 = -k_q(Q' - Q'_0) = \\ -k_q \frac{X}{Z}(Q - Q_0) - k_q \frac{R}{Z}(P - P_0) \end{gathered} \tag{3}$$

where $Z = \sqrt{R^2 + X^2}$. In these equations k_p and k_q are the coefficients of these characteristic and they are calculated from the regulating range of the virtual power flows.

5 QUALITY PARAMETERS CONTROL

The frequency and voltage values are controlled by primary (PR) and secondary (SR) control. Tertiary control may also be used.

The graph in Fig. 6 shows the primary and secondary frequency control which are activated after the load increase in the stand alone mode of the microgrid. The power balance is restored due to the primary control. The new steady state is at point two. The frequency (voltage) value is within the permitted limits but it is not equal to its nominal value. This frequency deviation is removed by the secondary control.

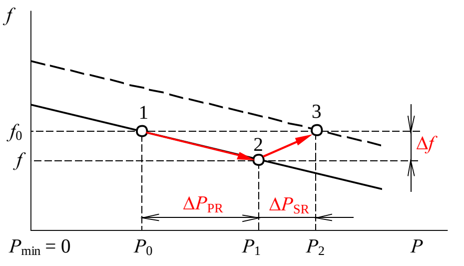

Fig. 6. Primary and secondary control principle

The secondary control is based on the change of the amount of electricity production. The nominal power is shifted from point P_0 to point P_2. It is mathematically determined by relationship [3, 5].

$$\frac{d}{dt} P_0 = PK_{\text{resp}}(f_0 - f) \tag{4}$$

Here, PK_{resp} is the coefficient of the secondary control that is calculated from the following equation

$$PK_{\text{resp}} = -\frac{1}{\tau k_p} \tag{5}$$

The speed of restoration of the nominal value depends on the value of the time constant τ.

The secondary control circuit is usually connected in parallel to the primary one. This basic configuration is presented in Fig. 7. Then the required output power from the source is given as the sum of the original nominal value and of the deviations from the regulating process.

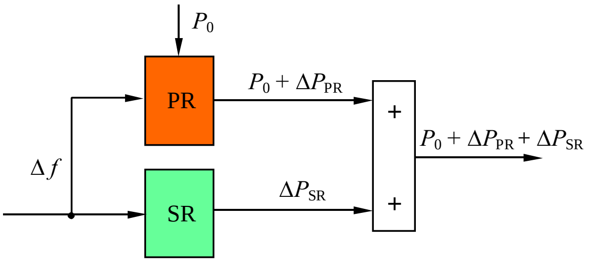

Fig. 7. Primary and secondary control circuit

6 SIMULATION MODEL

The voltage and frequency secondary control using the virtual power method during islanded microgrid operation is evaluated. The efficiency of the secondary control is verified by the change of the power demand. The basic model in Fig. 8 is composed of one PV system operating at a point different from MPP, of the line and of three resistive loads. The PV generator is designed as a current source. Parameters of this model parts which had been created in MATLAB Simulink are listed in Table 1.

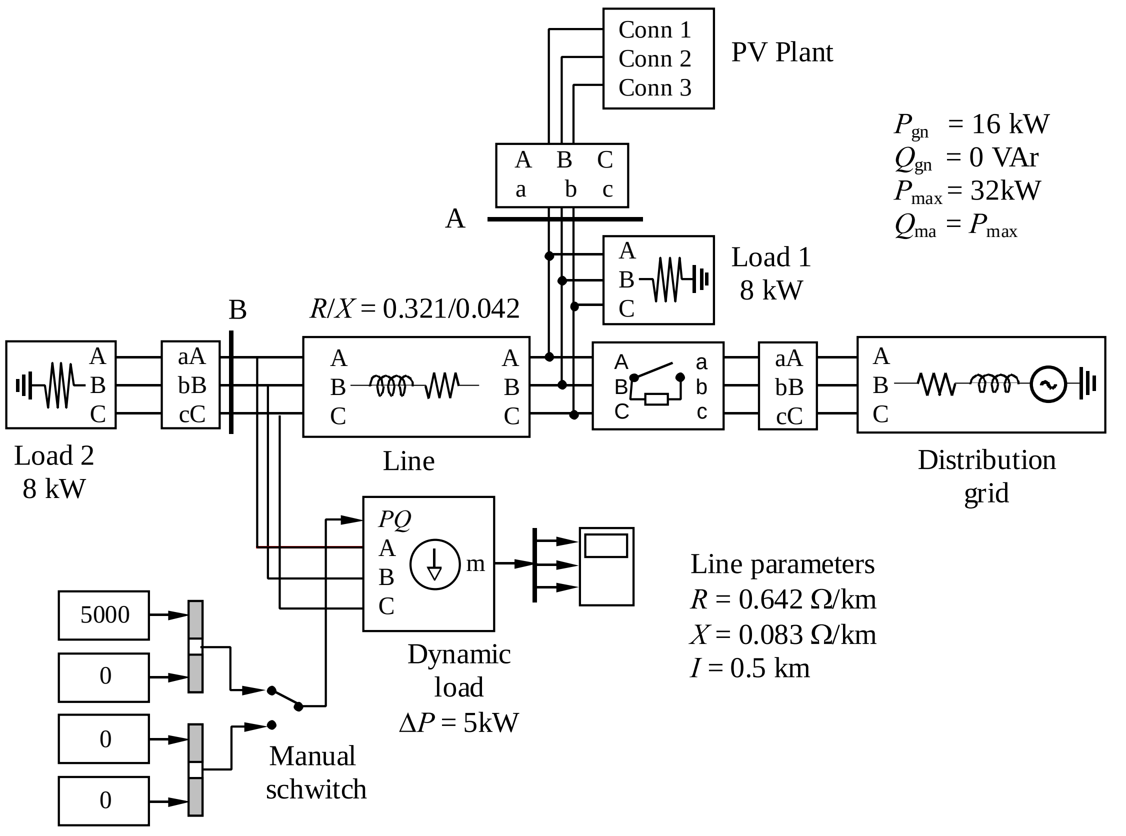

Fig. 8. Simulation model in MATLAB Simulink

Table 1. Model parameters

Parameter	Dimension	Value
Maximal real power output	kW	32
Nominal real power output	kW	16
Nominal reactive power output	VAr	0
Internal PV generator reactance	Ω	16.3
Interconnected PV capacitance	μF	1390.7
Connected filter inductance	mH	17
Connected filter capacitance	μF	15
Power line reactance	Ω/km	0.083
Power line resistance	Ω/km	0.642
Nominal voltage	V	230

The PV generator includes a three-phase voltage IGBT inverter and an LC filter. The Phase-Locked Loop (PLL) provides synchronization with the distribution network

The second simulation verification of the power sharing between two sources, created by connection of the same photovoltaic power plant to bus A and in the next simulation to bus B. In both cases the load is changed on bus B.

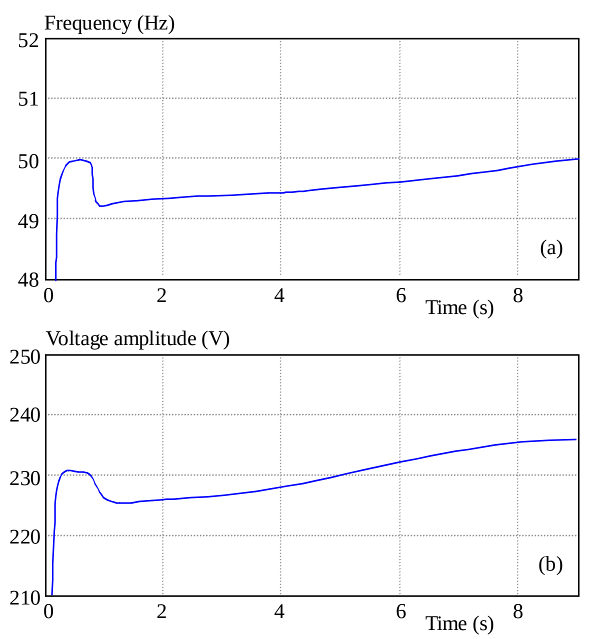

Fig. 9. Frequency and voltage control with $\tau = 3$ s

7 SIMULATION RESULTS AND DISCUSSION

The obtained results are in accordance with the above mentioned theory. At the beginning of the simulation, the

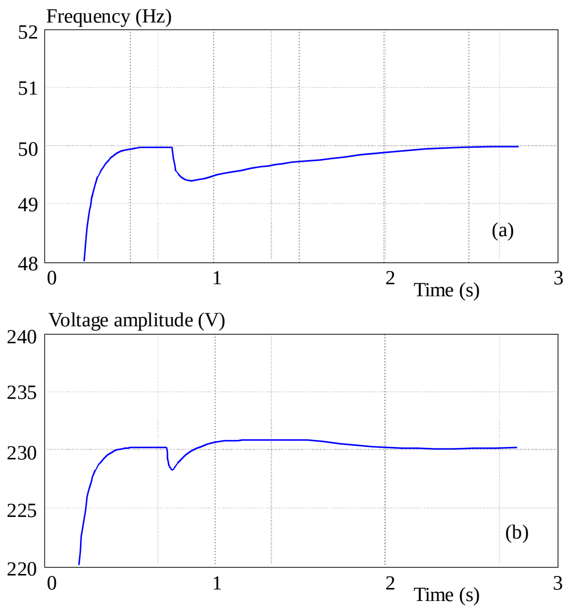

Fig. 10. Frequency and voltage control with $\tau = 3$ s

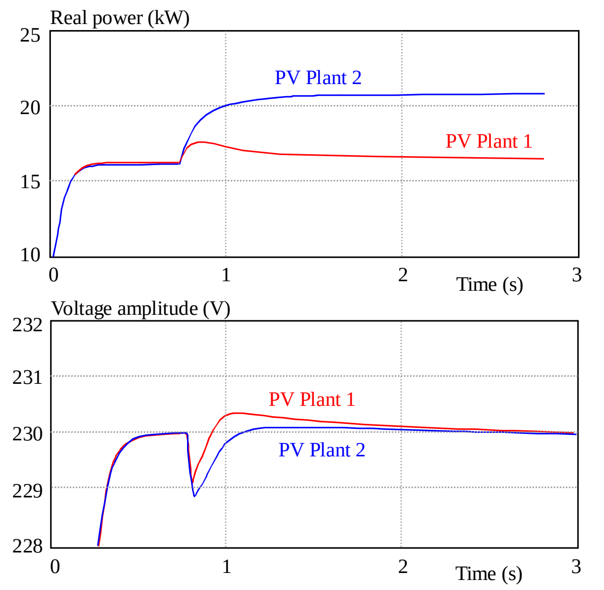

Fig. 12. Real power and voltage amplitude resulting waveforms provided the two photovoltaic power plants are not connected to the same bus

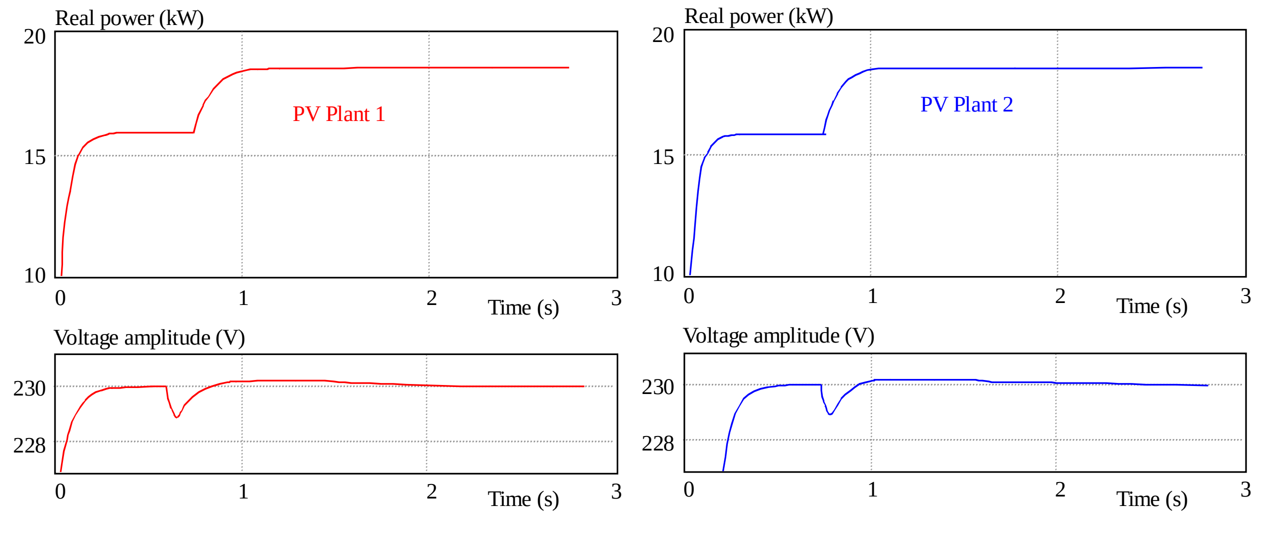

Fig. 11. Real power and voltage amplitude resulting waveforms provided the both photovoltaic power plants are connected to bus A

supply was equal to the demand. Approximately at time $t = 0.7$ s the load increased by 5 kW and thereby the frequency and voltage decreased. The restoration speed of the frequency and voltage nominal values is dependent on the time constant. The graphs in Fig. 9 show the waveforms of the voltage and frequency provided by the time constant of 3 s. Due to the primary control the new steady states correspond to 49.8 Hz and 225 V. Then the secondary control was activated and the nominal values deviations began to decrease.

The frequency and voltage regulation take place simultaneously and their regulatory circuits interact with each other. Therefore, the voltage is not stabilized on its nominal value, but its magnitude increases until the rated frequency value is achieved. Then the voltage value is much over its nominal magnitude. The continued growth of the voltage can be eliminated, for example by changing the coefficient of the secondary control and by limitation of the maximum reactive power supply from the sources. If the time constant is 0.03 s and the maximal reactive power output is 10 kVAr, the waveforms of the voltage and frequency are presented in Fig. 10. In the graphs in Fig. 11 the situation is seen, when two photovoltaic power stations with the same technical parameters are connected to bus A. At time $t = 0.7$ s the load is increased by 5 kW and the power sharing between these generators is equivalent.

On the other hand, in the case presented in Fig. 12, when the second photovoltaic power system is on bus B, power sharing between these plants is poor. This is due to the line impedance between the sources and the higher voltage drop on bus B than on bus A.

8 CONCLUSION

The aim of this paper was to evaluate the utilization of the photovoltaic power plants for the frequency and voltage control in islanded microgrids by means of the virtual active and reactive powers method. Important prerequisites for participation of the PV generators in the regulation process is their permanent operation outside off MPP and that the required power control is always available, for example due to a storage device.

The graphs show that the simulation results correspond to the theoretical assumptions. When the microgrid operates in the island mode, the primary control will ensure voltage and frequency values in the limit range and activation of the secondary control will restore their nominal values.

If there are two sources with identical drop control characteristics and coefficients in the islanded microgrid, then the load distribution will be accurate only if these sources are connected to one bus. In the case they are connected to different buses, the power sharing between them is calculated by the virtual output impedance.

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