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Reactive Power Compensation for Preventing Voltage Instabilities in Distribution Lines Enriched with PV Power Plants

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Abstract. The efficient voltage regulation method by capacitive reactive power usage is represented in the article. The stochastic electricity generation of multiple PV stations placed in local distribution lines induces voltage instabilities. These voltage fluctuations may overcome the allowable limits and cause technical problems and economic losses. The method of applying reactive power generated by a capacitor bank at the load is proposed. Primarily, a strict analytical solution of non-linear equations describing voltage deviations in the distribution line connected with photovoltaic systems was obtained. The control system can fast select optimal capacitors based on the analytical solution and then connect them smoothly to a load. The developed experimental setup verified and approved the correctness and accuracy of theoretical analysis. Experimental measurements confirmed the proposed method's ability to improve voltage stability in distribution grids. The proposed method is supposed to be used together with the transformer tap-changers in electrical substations. The capacitive power is applied in a time of inappropriate voltage deviations only and is disconnected as the tap-changer corrected the transformation ratio.

Keywords. Voltage instabilities, distribution lines, PV power stations, capacitive reactive power, voltage regulation.

1. Introduction

Solar photovoltaic (PV) electricity increases significant attention since it lowers electricity costs, and preserves environmental degradation, and other positive factors. The introduction of PV power plants in distribution lines takes a ramp-up trend during the last decade. However, substantial use of solar systems having significant stochastic output causes the reduced quality of electricity supply in distribution lines. The absence of fast voltage control leads to low voltage stability and the necessity to disconnect renewable energy generating facilities from the grid [1]. These circumstances are a significant threat to the operation of many electronic systems and limit renewable power production. Besides, short-circuit and other faults are also responsible for voltage instabilities.

Because of stochastic volatile behavior, the precise power balance between the load and source is nearly impossible. To decrease voltage fluctuations each transformer at every substation is equipped with a tap-changer. However, conventional tap-changers cannot compensate for the rapid disparities between generated and consumed power because of the sluggish dynamic response (~7-10 s) [2]. In the absence of other possibilities, electrical companies are forced to disconnect PV stations or diminish artificially power generation, which leads to economic losses and restricted profitability. Previously, several solutions are proposed and discussed to prevent voltage instabilities of the distribution lines [3-8]. The reactive power application methodology to mitigate voltage instabilities seems more efficient and cost-effective [9]. It is also emphasized that these methods are especially efficient for the distribution lines connected with many PV power plants [10-20]. The capacitive reactive power is generated through the capacitance-producing devices serially or shunt connected to a load [11]. A significant amount of studies was devoted to the methods to produce reactive power, such as DSTATCOMs [12, 13], STATCOM [4, 10,14], and real electrical capacitors [15]. Many innovative control techniques and algorithms have also been proposed to control reactive power flow [16-20].

It is found that the source current enhances significantly during the capacitive power application [2], which restricts the time duration to apply this method. As a result, these methods can be applied together with the tap-changers functionality. But an efficient control system is needed for the simultaneous operation of tap-changer and reactive power switching. It was stated that electronic devices (e.g., STATCOM, DSTATCOM) are useful to solve this issue [10, 12]; however, these appliances are rather expensive and are not reliable enough. A significant drawback of the method is the appearance of transient responses during capacitor switching (on/off). The transient process of capacitor switching should be smoothed as much as possible. The automatic switching of capacitors during voltage instabilities also remains unanswered. A strict mathematical analysis is required for the optimal selection of capacitance. The analytical results will also help to develop a control system for capacitor switching according to voltage instabilities. More importantly, these issues did not attract enough attention and should be solved.

This article aims to describe voltage instability phenomena and enumerate preventive and curative countermeasures. The main novelty is to consider that the additional power generation facilities relate to loads at the end of the distribution line. Such considerations give significant mathematical difficulties to getting strict analytical results, which are solved in this work. Also, a more accurate and efficient method for the assessment of required capacitances is developed. The dynamic process of voltage and current variations during connection/disconnection of capacitance is also studied analytically and experimentally. The evaluation of the control algorithm is suggested to be implemented by the connecting-disconnecting of real capacitors for the distribution line. As a result, such type a system represents a cheap, reliable, and a solution with long service life.

2. Analytical Solution

The equivalent circuit of a distribution line is represented in Fig. 1. Let us assume that the distribution line consists of the supply distribution transformer at the beginning and an equivalent load at the end. It is also assumed that several PV power plants are also connected to the load. In Fig. 1, the input voltage, distribution line, PV system, load, and compensating capacitor are highlighted by different blocks.

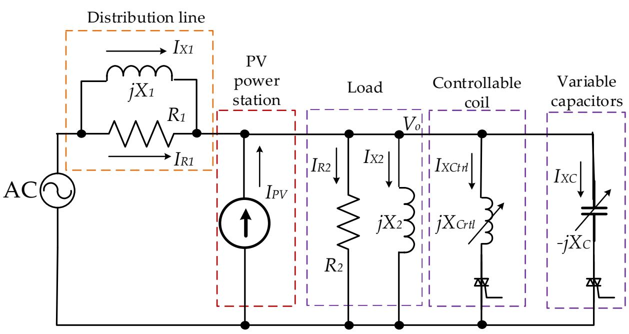


Fig. 1. The equivalent circuit of a distribution line relates to a distribution transformer, an equivalent load, and PV plants. The parameters of the equivalent circuit are designated as: V_S- source voltage, I_{R1}- the active component of current in the distribution line, I_{X1}- reactive component of current in the distribution line, I_{PV}- current of PV source, I_{R2}- active load current, I_{X2} - reactive load current, X_C- reactance of capacitance, I_{XC} - capacitor current, V_O- output voltage.

According to the nodal theorem, the impedance of the line is represented by parallel connected resistance R_1 and reactance X_1. Similarly, the load is denoted by parallel connected resistance R_2 and a reactance X_2. The capacitor having a reactance X_C is connected to the load for improvement of load voltage. The nodal circuit approach provides the following equation:

$$\frac{\dot{V}_S - V_0}{jX_1} + \frac{\dot{V}_S - V_0}{R_1} + I_{pv} - \frac{V_0}{R_2} + \frac{jV_0}{X_2} - \frac{V_0}{-jX_C} = 0 \qquad (1)$$

For simplicity, the load voltage (V) identifies as a complex number with a phase angle equal to zero; therefore, it can be represented as a real number. As a result, the current of a PV source can be simply estimated as $I_{pv}=P/V_0$. Equation (1) can be written as:

$$\frac{\dot{V}_S - V_0}{jX_1} + \frac{\dot{V}_S - V_0}{R_1} + \frac{P}{V_0} - \frac{V_0}{R_2} + \frac{jV_0}{X_2} - \frac{V_0}{-jX_C} = 0 \qquad (2)$$

With the following coefficients:

$$\frac{1}{R_1} = G_1, \frac{1}{R_2} = G_2, \frac{1}{X_1} = Y_1, \frac{1}{X_2} = Y_2, \frac{1}{X_C} = Y_C, \qquad (3)$$

The equation (2) can be solved and its solution regarding magnification of a relative output voltage is as follows:

$$\chi^2 = \frac{A + \sqrt{A^2 - G_P^2 B^2}}{B}; \; A = (G_1 + G_2)G_P + \frac{1}{2}(G_1^2 + Y_1^2); \qquad (4)$$
$$B = (G_1 + G_2)^2 + (Y_1 + Y_2 - Y_C)^2$$

The relative voltage regulation should be obtained as the Eq. (13) square root. For the following parameters of a distribution line: R_1=40 Ω, X_1=13.3 Ω, R_2=104 Ω, X_2=520 Ω, and for grid 50 Hz, the relative output voltage versus capacitance is shown in Fig. 2.

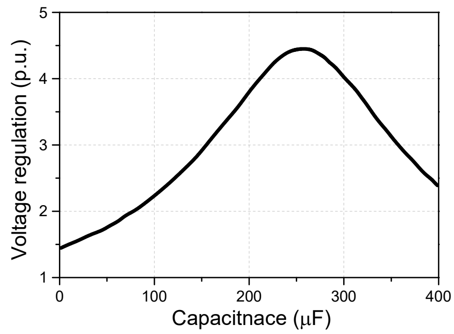


Fig. 2. Relative voltage changes vs capacitance of the load. The capacitor relates to the load.

A maximum magnification effect can be determined by the solution of the derivative of χ^2 concerning capacitance equalized to zero. The result of this solution gives an optimal capacitance C_{opt}:

$$Y_C = Y_1 + Y_2 \Rightarrow C_{opt} = \frac{Y_1 + Y_2}{\omega} \qquad (5)$$

The maximum amplification effect of output voltage for the optimal capacitance is as follows:

$$\chi_{max} = \frac{\sqrt{A + \sqrt{A^2 - G_P^2 (G_1 + G_2)^2}}}{(G_1 + G_2)} \qquad (6)$$

It is worth reminding that the amplification effect can achieve 4-4.5 magnitude.

For engineering applications, it is important to calculate the magnitude of the source current I_S. It is calculated as a solution to the following equation:

$$\dot{I}_S = \frac{\chi V_S}{R_2} - j\frac{\chi V_S}{X_2} + \frac{j\chi V_S}{X_C} - \frac{P}{\chi V_S} \qquad (7)$$

The dimensionless solution of the I_S regarding current I_b obtained for C=0 is as follows:

$$\frac{I_S}{I_b} = \sqrt{\left(\chi - \frac{P \cdot R_2}{\chi V_S^2}\right)^2 + \chi^2 R_2^2 \left(\frac{1}{X_2} - \frac{1}{X_C}\right)^2} \qquad (8)$$

Fig. 3 shows the relative enhancement of load voltage and source current as a function of capacitance. It is important to note that the voltage enhancement is accompanied by the increase of source current, which is the inevitable complement for voltage improvement.

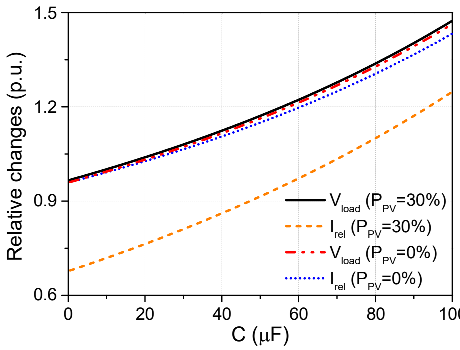


Fig. 3. The relative increase of load voltage and source current as of the capacitance increases for PV power of 0% and 30%.

The important question remains unanswered about the selection of capacitance to provide the required voltage magnification. The voltage magnification is assigned as $\lambda_r = (V_0/V_s)2$, which can be obtained by solving Eq.(4). Simplified Eq. (4) can be written as:

$$\lambda_r \frac{B}{A} = 1 + \sqrt{1 - \frac{G_P^2 B}{A^2}} \qquad (9)$$

Were parameters A, and B as in Eq. (4).

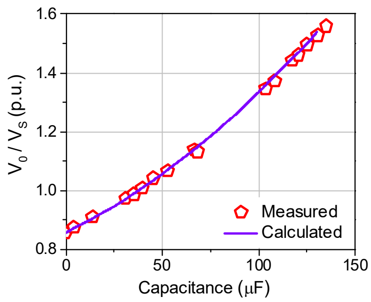
Solution Eq. (9) with regards to capacitance value ensuring required magnification effect gives:

$$Y_C \sim= Y_1 + Y_2 - \sqrt{\frac{A}{\lambda_r} - (G_1 + G_2)^2} \qquad (10)$$

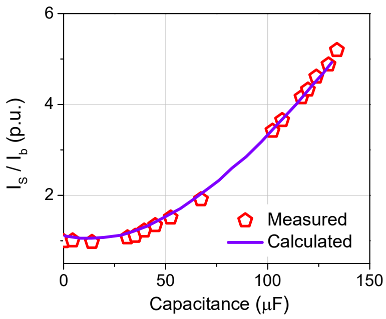
Analytical expression (10) can determine the capacitance of a capacitors bank required to prevent existing voltage instability at the load connection in the distribution line. This circumstance founds the control principle of voltage stabilization. Firstly, the control system estimates all included in formula (10) parameters through permanent measurements of load voltage and power, and the power of generating facilities (PV stations). The control system follows voltage fluctuation in the distribution line and calculates the required capacitance for the connection in the event of exaggerated voltage deviation. Further, a control system chooses those capacitors which consist of required capacitance and electronically join them to the load. Chosen capacitors from a bank are connected at the beginning or at the end of an AC period to prevent unwanted transient processes from diminishing power quality. A detailed description of voltage control will be explained later. Now the analytical solution of Eq. (4) is verified experimentally. Fig. 4 shows the experimental setup for this study. The dynamic process of voltage and current The changes during capacitor connection-disconnection to the load is also studied.

Fig. 4. Experimental setup for the voltage measurements (1- additional active load, 2-reactive load, 3- active load, 4- line, 5- variate, 6-, 7- capacitor bank).

The experimental setup includes a voltage source (adjustable regulator transformer, 0-250 V, 1500 VA), six Analog Input Module for the MOSCAD-L RTU, Handheld Power Quality Analyzer, an equivalent consumer impedance, and additional laboratory equipment. A coil was wound on the ferromagnetic core to design the distribution line. The air gap ensures the linearity of the impedance. The equivalent impedance of the modeled distribution line is R_g= 5.66 Ω, X_g= 15.6 Ω. The load was simulated by regulated laboratory inductance, which provides the range of resistance and reactance from 50-200 Ω and 5-100 mH. The capacitance bank has five capacitors with capacitances of 4.4 μF, 9.9 μF, 17.1 μF, 35.4 μF, and 64.8 μF. It is important to note here that the capacitance values are arranged approximately in binary order. All of them have individual switches allowing a total of 32 combinations of different capacitances. Therefore, on/off toggling allows uniform control of reactive power at the end of a line. Verification carried out showed the correspondence of the analytical and experimental results and can be seen in Fig.5 (a, b).



a)



b)

Fig.5. Comparison between measured data of current increase vs. capacitance rise. Open symbols and solid lines represent the experimental and calculated data, respectively.

3. Methodology of a control system

The control system to verify the proposed method is simulated using the PSIM software (Fig. 4). The control system includes a chain of R_{load}-L_{load} bank of capacitors, a sub-circuit for estimation of load impedance, a sub-circuit of control, and capacitors switching. In the capacitor bank, the capacitors are arranged in a binary order of capacitances. The distribution line is represented by lumped elements R_{line}-L_{line} connected in parallel. Two power sources are connected: with nominal voltage, and the other is with a lower voltage.

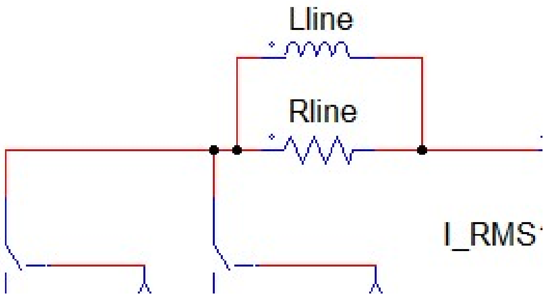


Fig. 5. PSIM model of a control system to voltage control by connecting-disconnecting capacitors.

Fig. 6 presents the output simulated characteristics of the control system. The control system works as follows. The estimation block calculates the load voltage, current, power, impedance, resistance, and reactance by the permanent measurements. The load voltage is measured during each half or one period of AC. It is carried out by acquiring several instantaneous voltage magnitudes during the half or one period of AC. The control system approximates these points by a sinusoidal function that testifies root-mean-square (rms) voltage amplitude. These steps ensure the fastest response time needed to improve the voltage level. The load parameters are altered relatively slower rate. Hence, the impedance, resistance, and reactance of load are estimated by the measurements for a prolonged time, approximately several hundred periods. All information mentioned above is transferred to the control circuit. The control circuit compares the total generated PV power and load voltage with the rated value. Now, capacitance magnitude is decided using eq. (28) as per the voltage fluctuations. Further, special capacitors from the bank (C1…C5) are selected, which provide the required capacitance. The control system connects the capacitors to the load and continues this connection until the voltage remains within the allowable limits. If load voltage again changes from the nominal range, the system re-calculates the required capacitance according to present circumstances and connects the required capacitance. Tap-changer begins to increase or decrease the transformation ratio. Each stage may take approximately 7-10s depending on the type of tap-changer, and the average time of voltage stabilization takes about 100-120 s. During this time, the control system modifies the value of capacitance connected to the load since the voltage is changing when the tap-changer is gradually shifting the transformation ratio. As the voltage achieves the nominal level, the system disconnects capacitors from the load. Therefore, the total duration for one event of voltage instabilities to the nominal one should not exceed ~30-120s.

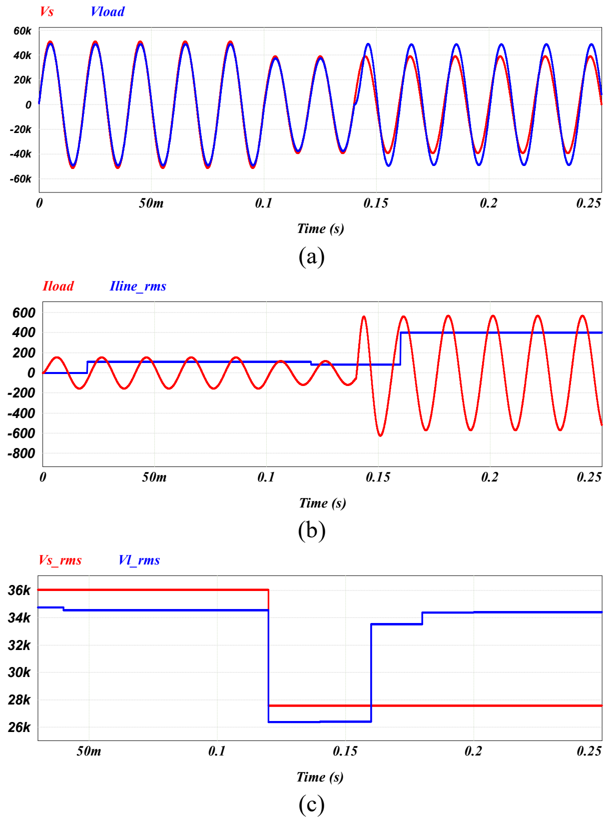


Fig. 6. Simulated results of control system functionality. (a) Source and load voltage behavior, (b) Current in the load and distribution line, (c) source and load rms voltage.

4. Results and Discussion

Later, a control system was modeled on the experimental setup including a regulating voltage source, a physical model of a distribution line, load, and a bank of capacitors with electronic switches (Triacs). An experimental study showed PSIM model adequacy to real processes in the system. In addition, the experimental verification of a dynamic characteristic during capacitor switching was carried out and the results are shown in Fig.7. Obtained results ensure the possibility and efficiency of the proposed voltage control.

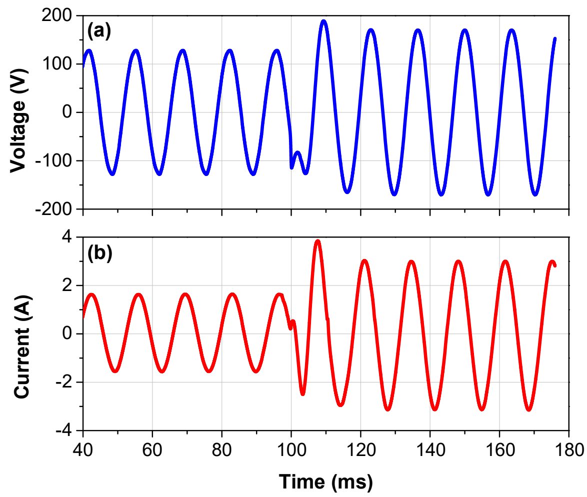


Fig. 7. Voltage and current dynamic response during capacitor switching. These curves represent the measured voltage and current behavior during capacitors' connection to a load.

5. Conclusions

This article presents an efficient method to prevent voltage instabilities in the power distribution lines. The main novelty of the proposed approach is the fastest response time (only one or two periods). A strict analytical solution of non-linear equations describing the parameters of the distribution line is obtained to allow such a fast response. Another novelty is the development of a more accurate and efficient method for the assessment of required capacitances. The experimental results show good agreement with the theoretical approach for both steady-state and dynamic analysis. The control system is designed and studied for the smooth transient process of capacitor switching. It is suggested that the transient process can be smoothed significantly if the capacitors are connected at the end or beginning of a voltage period. The TRIAC switching appliances are used to ensure the connection/disconnection of capacitors at the optimal time providing admissible transient processes. Both analytical and experimental results show that source current enhances substantially with the voltage changes. Hence, it is recommended to apply capacitive reactive power for a short period of ~40-120 s. This period is enough for the tap-changers to correct the transformation ratio. It should be emphasized in addition, that this type of control system represents a very cheap technical solution with significant reliability and long service life.

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