REACTIVE POWER COMPENSATION OF SELF-INDUCED VOLTAGE VARIATIONS

Ara PANOSYAN
GE Global Research – Germany
panosyan@ge.com

Reigh WALLING
GE Energy – USA
reigh.walling@ge.com

Eva-Maria BÄRTHLEIN
TUM – Germany
eva.baerthlein@mytum.de

Rolf WITZMANN
TUM – Germany
rolf.witzmann@tum.de

ABSTRACT

The significant increase in renewable energy resources in distribution networks has introduced novel technical challenges to distribution system design and operation. The integration of intermittent DGs, like solar and wind, into the distribution network poses a challenge to the traditional voltage regulation strategies due to the alteration of power flow patterns, and the variability of the DG output.

It is now commonly accepted that a high level of renewables penetration into the distribution networks would ultimately require the participation of DGs in voltage regulation. To date, no ideal approach exists for how the DGs can best contribute to the voltage regulation.

This paper presents a new reactive power regulation method for the compensation of self-induced voltage variations. The proposed approach achieves sufficiently accurate voltage compensation with very little to no communication requirements. A further significant advantage is that this approach does not violate the restrictions imposed by standards.

INTRODUCTION

Recent years have seen rapid growth in distributed generation (DG) worldwide. Photovoltaic (PV) generation connected at the distribution level make up a large part of the DG capacity. This trend poses major challenges for electrical power systems, which were originally not designed for such distributed and variable power generation.
Conventionally, the power flow in electrical grids is unidirectional. Current flows from large power generation units over the transmission and distribution grid to the end-costumer. Naturally, the impedance of a distribution feeder from the substation to the consumer causes a voltage drop. With distributed generation the power flow patterns are altered, and power flow may even become bidirectional. Reduction of the net load, and especially power reversal, can lead to voltage rises further away from the substation, especially at remote feeder ends. In terms of distributed renewable integration, the high degree of power intermittency results in voltage variations which are particularly problematic for distribution networks.
Hitherto network voltage is controlled by a combination of On-Load Tap Changers (OLTC) and switched capacitor banks. This proved to be an efficient way to mitigate the slow voltage variations solely caused by the power demand of loads usually following a daily pattern [1]. OLTC and switched capacitor banks are also capable of mitigating the voltage changes caused by non-intermittent distributed generation. With the increasing number of intermittent energy generation, however, this concept is not feasible anymore. Alternative voltage control methods need to come into focus. The method introduced in the paper at hand makes use of the inverter connected to the renewable generation unit for reactive power compensation. By adjusting the power factor according to active power injection and loading condition, self-induced voltage variations are compensated.

REACTIVE POWER COMPENSATION

By utilizing the renewable generator's inverter as a reactive power sink, the voltage increase caused by DG can be counteracted. There are several approaches to this reactive power compensation.

Closed-Loop Voltage Control

The most straightforward solution is the closed-loop voltage regulation, where reactive power demand is actively adjusted directly based on the voltage deviation from a fixed reference voltage.
There are however several disadvantages to this method. First, stability issues may arise. The voltage regulator of the inverter may adversely interact both with other converter voltage controls and with utility voltage regulators. This is one of the reasons why closed-loop voltage control is prohibited by the IEEE Standard 1547 [2]. Second, in order to control the voltage, the inverter may attempt to compensate the reactive power demand of the loads, which would necessitate large reactive power capabilities.

Constant Power Factor Compensation

The constant power factor (PF) compensation is an open-loop voltage regulation method for compensating self-induced voltage variations at the point of interconnection (POI).

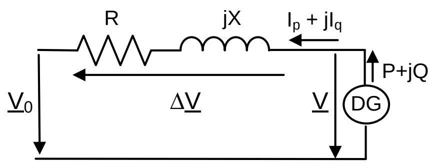

Figure 1 - Voltage rise caused by distributed generation

Assuming the simplified equivalent circuit in Figure 1 between the DG's POI ($\underline{V}$) and the substation ($\underline{V}_0$), the voltage variation $\Delta\underline{V}$ at the POI due to the active (P) and reactive (Q) power of the DG is given by

$$\begin{aligned} \Delta\underline{V} &= \underline{V} - \underline{V}_0 \\ &= (I_p R - I_q X) + j(I_p X + I_q R) \\ &= \left(\frac{P}{V}R + \frac{Q}{V}X\right) + j\left(\frac{P}{V}X - \frac{Q}{V}R\right) \end{aligned} \qquad (1)$$

Where I_p and I_q are the active and reactive currents injected by the DG, and R and X are the driving-point resistance and reactance at the POI. It can be seen from the voltage phasor diagram in Figure 2 that the change in the voltage magnitude $|\underline{V}| - |\underline{V}_0|$ is primarily due to $I_p R$ and $I_q X$, whereas $I_p X$ and $I_q R$ have minor impact on the voltage magnitude and mainly effect the phase shift between $\underline{V}$ and $\underline{V}_0$. An approximation of the voltage variation at POI can hence be obtained by neglecting the imaginary part of Eq. (1) as follows

$$|\underline{V}| - |\underline{V}_0| \approx I_p R - I_q X = \left(\frac{P}{V}R + \frac{Q}{V}X\right) \qquad (2)$$

A full compensation of the voltage magnitude variation based on this approximation would be achieved by setting Eq.(2) to zero. This corresponds to a constant power factor

$$PF \approx \cos\left(tan^{-1}\left(\frac{R}{X}\right)\right) \qquad (3)$$

This approximation yields relatively precise voltage variation mitigation ($|\underline{V}| - |\underline{V}_0| \approx 0$) for certain network configurations and states. Any changes in loading conditions or network topology, however, may lead to high inaccuracies. Moreover, at high power levels the effect of the neglected term becomes more significant and the approximation leads to over-compensation of the self-induced voltage increase.

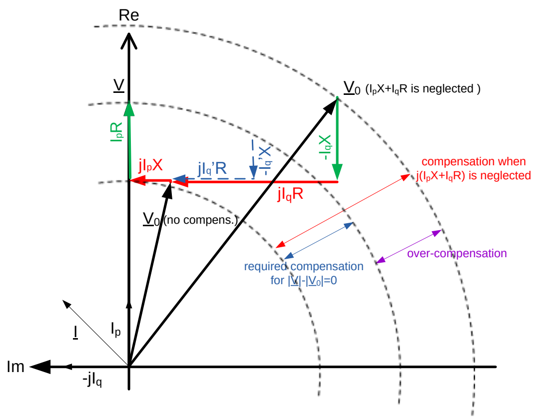

Figure 2- Schematic voltage phasor diagram

Variable Power Factor Compensation

The exact amount of reactive compensation (I_q) needed for $|\underline{V}| - |\underline{V}_0| = 0$ can be determined by solving the quadratic equation (Eq. (4)), which can be derived from the voltage phasor diagram in Figure 2.

$$\begin{aligned} |\underline{V}| - |\underline{V}_0| = (R^2 + X^2)I_q^2 + 2VXI_q + \\ (R^2 + X^2)I_p^2 - 2VRI_p = 0 \end{aligned} \qquad (4)$$

The reactive compensation would therefore correspond to a variable power factor, which results in an accurate compensation of the self-induced voltage variations.

It should however be remembered, that equation Eq. (4) is based on the simplified equivalent circuit in Figure 1. Therefore, the accurate amount of reactive compensation (I_q) needed for the self-induced voltage variation ($|\underline{V}| - |\underline{V}_0|$) depends not only on the active power output of the DG (I_p), but also on the state of the network. The latter could be represented in Eq. (4) by a variable driving-point impedance, which is a function of the network state. The values of R, X would therefore vary with the variation of loads and generation, as well as for any switching operation in the network.

There are several advantages to the variable power factor control method. Compared to the constant power factor voltage control method, the voltage is not over-compensated resulting in a reduction of network losses due to the reduction of reactive power flow. Unlike some other voltage control concepts, this method does not necessitate costly communication infrastructure, thereby ensuring a high level of reliability. Furthermore, stability issues can be avoided, as it is not a voltage based control (i.e. closed-loop voltage control). Lastly, by only regarding the self-induced voltage variation, the inverter does not mitigate the influence of other DGs in the network. Thus, individual converter losses are reduced and acceptance by inverter operators is increased.

METHOD FOR COMPUTING VARIABLE POWER FACTOR CURVES

As can be deduced from Eq. (4), the relationship between the active power inducing voltage variations and the reactive power required to compensate these variations is quadratic. The Q-P relationship can hence be given as a non-linear curve, which depends on the state of the network. The Q-P curve for each DG unit for a certain loading condition can be obtained as follows.

First the voltage at the DG's POI at zero DG power output is computed through an exact load flow calculation. This represents the expected POI voltage at a certain network state in the absence of the considered DG. The DG bus is set to closed-loop voltage control mode, with the voltage reference set at the previously computed POI voltage at zero power. The active power output of the DG is then stepwise ramped up from zero to maximum power, and the reactive power required to regulate the voltage to the reference value is saved for each load flow simulation step (i.e. active power output). An example of such Q-P curves for three loading conditions are shown in Figure 3.

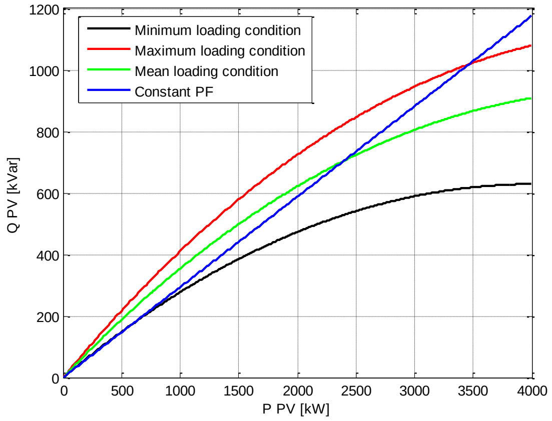

Figure 3 – Reactive-to-active power relationship

The difference between the two curves representing the boundary cases (i.e. min and max loading conditions) is largest at maximum DG power output. Hence, if a single Q-P curve is to be pre-defined for each DG and week day, the Q-P curve could be calculated for the prevailing network loading condition at the period of maximum DG output (e.g. around noon for PV). Compensation inaccuracies due to the deviation from the exact Q-P curve can herewith be minimized.

In comparison with the constant power factor curve derived from the R/X ratio of the driving-point impedance, it is apparent that, depending on the state of the network, the constant power factor approximation can lead to either under-compensation at low output levels, or over-compensation at high power output levels.

Any changes in the network topology or transformer tap changing can however have adverse impact on the compensation accuracy. This can be avoided if the Q-P curves could be updated on a periodic basis, for instance at a similar frequency as of a distribution management system (e.g. every 10 minutes).

A further improvement in accuracy is achievable if a load forecast (e.g. daily or weekly) is available and therefore the dependency of the Q-P curves on the loading condition can be captured adequately. Furthermore, since OLTCs are in many cases dispatched based on the load forecast, the impact of tap changing on the Q-P curves can also be considered correctly.

The Q-P curves based on a 24 hour load forecast with 15-minute resolution are illustrated in Figure 4. It can be seen from the curves how the effects of tap changing events at around 11AM and 2PM are properly taken into account, and how the impact of load variation on the Q-P curves reactive power is largest at high DG power output.

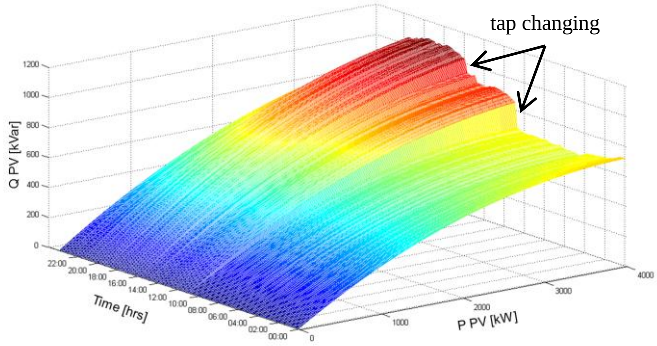

Figure 4 – Three-dimensional Q-P curve

CASE STUDY

The performance of the variable power factor compensation based on the availability of load forecast is compared to the constant power factor compensation, as well as to the variable power factor compensation with no load forecast.

The simulation is performed on a typical 13.24 kV U.S. medium-voltage grid with 216 nodes. A 4 MW PV power plant is connected via step-up transformer near the remote end of a feeder. Additionally, 93 loads with a total peak power of 9.5 MW are distributed throughout the network.

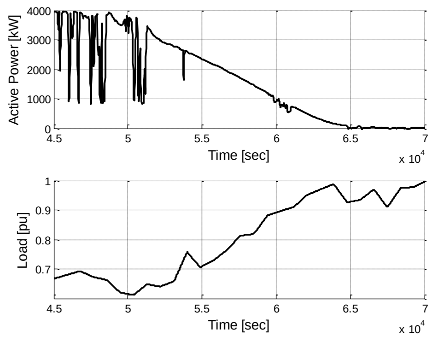

Figure 5 – PV and load profile

The simulation is performed for a period of 7 hours (12:30 to 7:30 PM). The power output of the PV plant and the total load variation during this time is assumed to follow the profiles shown in Figure 5.

The Q-P curve applied for the variable power factor compensation method with no load forecast is calculated for 0.65 pu loading, which is roughly the loading level during the period of maximum PV output. For the simulation it is further assumed that all loads follow the same variation, and that a perfect load forecast is available. The high-voltage terminal of the step-up transformer is chosen as the POI, where the voltage reference for the computation of the Q-P curves is set. The resulting voltage curves at the PV POI are plotted in Figure 6.

The case without PV serves as a base case for comparing the performance of the different compensation methods. The impact of the PV plant on the voltage rise and variations is illustrated by the case of PV without reactive power compensation.

The performance of the constant power factor method depends on the output level of the PV plant. The constant power factor achieves highly accurate compensation of the self-induced voltage variation at low levels of PV output (e.g. second half of the simulation window), but over-compensates during periods of high PV output (e.g. first half of the simulation window).

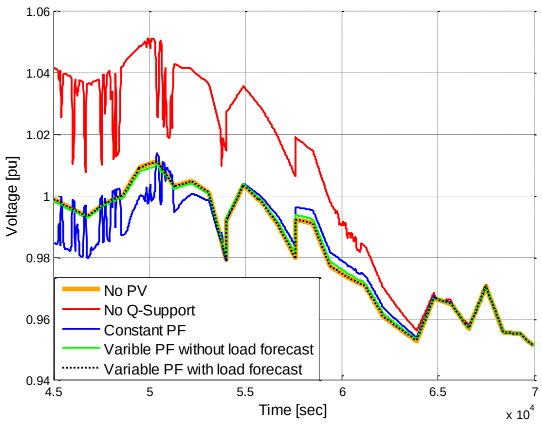

Figure 6 – Voltage at PV POI

The variable power factor compensation method with no load forecast achieves a highly accurate compensation of the self-induced voltage variations. This is due to the accuracy of the used Q-P curve during the period of high PV output, which coincides with a loading level close to 0.65 pu that was assumed for the Q-P curve's calculation. In the second half of the simulation window (after about 55000 sec), the loading level increases and the Q-P curve is thus less accurate. The reduction in accuracy however becomes uncritical, because of the simultaneous decrease in PV power output.

Finally, the variable power factor compensation concept with load forecast almost perfectly matches the voltage without any PV injection. This was expected, because of the simplifying assumption of a perfect forecast and the uniformly changing loads.

In Figure 7 the resulting voltage profile across the entire network for the instant of time with maximum DG power output is illustrated. It shows how the voltage remains very close to the reference case without PV not only locally at the POI, but across the complete distribution feeder.

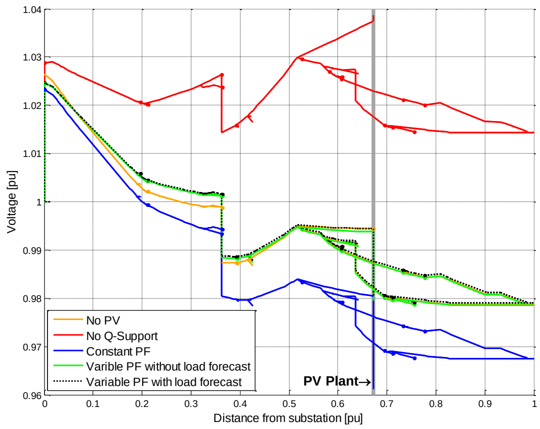

Figure 7 – Voltage profile across the entire network

CONCLUSION

The results of the simulations show that the constant power factor method could be a simple and fairly accurate method for compensating the self-induced voltage variations of DGs. Its accuracy however strongly depends on both the network loading condition, and the level of DG power.

Depending on the level of forecast availability, the proposed variable power factor compensation method can achieve almost perfect compensation with minor communication requirements. However, even in the absence of any communication, the much simpler variable power factor compensation method based on an estimated prevailing loading level at the period of maximum DG output can achieve a much more accurate compensation than the constant power factor method.

REFERENCES

[1] R. Walling, Z. Gao, 2011, "Eliminating Voltage Variation due to Distribution-Connected Renewable Generation", DISTRIBUTECH, San Diego.

[2] IEEE 1547-2003, "IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems", IEEE , 28-Jul-2003.