MITIGATING IMPACT OF LARGE-SCALE PV INTEGRATION ON MV DISTRIBUTION NETWORK WITH SEQUENTIAL CONTROL FUNCTIONS: A CASE STUDY IN NOORDWOLDE GRID, THE NETHERLANDS

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ABSTRACT

In this paper, the voltage violation problem that might arise from the integration of a large-scale PV system into a distribution network in Noordwolde, the Netherlands is investigated. Subsequently, a sequential control scheme is proposed that coordinates reactive power absorption and active power curtailment of PV inverter to mitigate such problem. The proposed control is locally performed at the inverters and does not require an extensive communication system. Its performance is compared with the control scheme employing only reactive power absorption or active power curtailment. The feasibility of the proposed control is successfully verified through simulations on Noordwolde medium voltage network using Vision Network Analysis along with data measurements in the field.

INTRODUCTION

Altered condition to conventional distribution networks with the addition of intermittent, non-dispatchable and high penetration of renewable energy sources, such as wind turbine and photovoltaic (PV), is creating new technical challenges to the network operation. One of the most popular challenges associated with the high penetration of PV is an undesirable voltage rise at the point of connection (POC) [1]. Voltage rise is exacerbated when the consumption is at its lowest and generation at its highest. A series of reports on the PV systems produced by the International Energy Agency revealed that voltage rise and overvoltage are two of the primarily concerned problems [2]. To conform to the voltage-characteristic standard, protective devices in the distribution network must be able to reduce the active power generation when voltage increases [2]. Without a proper mitigation strategy, overvoltage could cause severe damage to customers' electrical appliances and tripping of the PV systems [1]. An effective control methodology, thus, is of vital importance in maintaining the voltage levels and maximizing the active power generation of the PV systems [3]. This important issue is studied in this paper.

Various solutions have been studied to solve overvoltage problem in the distribution network, for example, cable reinforcement, transformer tap changer adjustment [4], utilization of voltage regulating devices, active power curtailment (APC) [5], and reactive power absorption (RPA) [6], [7]. Cable reinforcement needs huge investment cost and takes a long time to implement, thus it is not preferred to mitigate the overvoltage issues in a short time. Meanwhile, the adjustments of transformer tap changer cannot be frequently applied when the transformer is in operation because the MV/LV transformers are often equipped with off-load tap changers [8]. The traditional voltage regulating devices, such as line voltage regulators (VR) cannot typically act in short time-scale because of its inherent control methodology which includes gear-driven switching operations [3]. APC and RPA are recently emerging as the promising solutions to the overvoltage problems. These methods control the PV inverters to regulate its output power in response to the voltage level measured at the POC. These methods are locally implemented by the PV inverters and do not need an extensive communication system. Hence, these methods maximize the use of existing equipment in the network, i.e., the PV inverters.

In [5], droop-based APC control is proposed to mitigate the overvoltage problem in low voltage (LV) network due to the high PV penetration. It reveals that the droop-based APC is capable of effectively preventing the overvoltage problem because of the LV network being highly resistive. However, implementing APC to support voltage regulation is financially unprofitable for PV owners as it reduces PV power generation. Authors in [6] introduce a reactive power control to alleviate the fluctuation of voltage magnitude. Moreover, in [7], RPA based on reverse power flow is studied to tackle the voltage rise problem stemming from the surplus PV power generation. Nevertheless, the effectiveness of these reactive power control on the voltage level regulation significantly relies on the R/X ratio of the distribution network and the reactive power capacity of the inverters [9]. When solar irradiation is high, the PV inverters capacity will accommodate more active power output and less reactive power output. Therefore, applying only RPA is not able to yield the best voltage regulation. Meanwhile, authors in [9] combine RPA and APC to reduce the tap-changing operations of VR. In [10], coordinated control of RPA and APC is used for overvoltage mitigation in LV microgrids. This approach activates RPA prior to APC to solve overvoltage problem with the aim of minimizing the curtailed active power generation of PV. Having mainly aforementioned inspiration, this paper proposes the sequential RPA-APC control function to mitigate the impact of large-scale PV integration on the voltage level of medium voltage (MV) distribution network in Noorwolde, the Netherlands. The main controlling purpose is to minimize the curtailment of active power generation of PV.

THEORETICAL APPROACH

A PV inverter, which is capable of operating as a four-quadrant converter, can regulate the active and reactive power output. Since active and reactive power control has effect on voltage regulation, the voltage level at POC of the PV system can be regulated [9].

Active Power Curtailment (APC) Method

In this *P* - *V* droop-based APC method, the active power injection ($P_{injected}$) of the inverters to the grid is regulated as a linear function of voltage level measured at the POC (V_{POC}) as expressed below:

$$P_{injected} = \begin{cases} P_{\max} & \text{if } V_{\min} < V_{POC} \le V_{thP} \\ P_{\max} - P_{\max} \times \dfrac{V_{POC} - V_{thP}}{V_{max} - V_{thP}} & \text{if } V_{thP} < V_{POC} < V_{\max} \\ 0 & \text{if } V_{POC} \ge V_{\max} \end{cases} \quad (1)$$

where [V_{min} V_{max}] = [0.9 1.1] in p.u. to comply with the requirement standard EN 50610 [11].

As shown in (1), if V_{POC} is still lower than the active power curtailment voltage threshold (V_{thP}), the inverter operates at the maximum power point (P_{max}). If V_{POC} surpasses V_{thP}, the APC is activated to reduce $P_{injected}$.

Reactive Power Absorption (RPA) Method

In this *Q* - *V* droop-based RPA method, the desired reactive power absorbed by the inverter (Q_{absorb}) is a linear function of V_{POC} as shown in the following equation [10].

$$Q_{absorb} = \begin{cases} Q_{max} \times \dfrac{V_{POC} - V_{thQ}}{V_{max} - V_{thQ}} & \text{if } V_{thQ} < V_{POC} \le V_{\max} \\ 0 & \text{if } -V_{thQ} \le V_{POC} \le V_{thQ} \end{cases} \quad (2)$$

When V_{POC} exceeds the reactive power absorption voltage threshold (V_{thQ}), the RPA is triggered. The *Q* - *V* droop control then regulates the amount of Q_{absorb} with Q_{max} represents the maximum RPA of the inverters.

Sequential Control Method of RPA and APC

Figure 1 shows the sequential combination of *Q* - *V* droop-based RPA and *P* - *V* droop-based APC of the PV inverters to solve the overvoltage problems. This sequential control mechanism prioritizes the use of RPA, while APC is performed only as a last mean. When V_{POC} exceeds V_{thQ}, RPA starts absorbing the reactive power. If V_{POC} continues rising and crosses V_{thP}, APC is triggered and curtails the active power to reduce the voltage level at the POC.

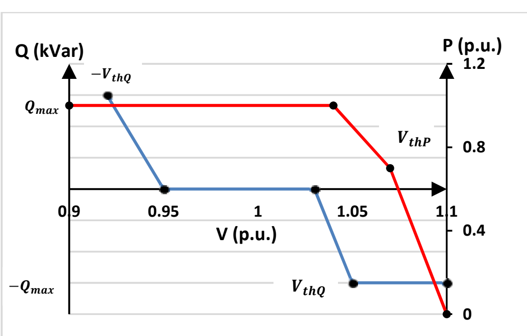

Figure 1. Sequential RPA-APC control of PV inverters.

TEST NETWORK AND DATA

To address the issues and the system behavior, load-flow analysis is implemented using Vision Network Analysis. Several parameters, models and boundaries that for the simulation are defined in this section.

Noordwolde MV Distribution Network

A 3.44MW PV system is newly installed in a 10.5/0.4 kV Noordwolde (NW) substation, the Netherlands as displayed in Figure 2. The new PV system is connected to NW substation via two POCs; each has the same capacity of active power generation of 1.72MW and reactive power output of 0.75MVAr. Figure 3 shows the detailed configuration network in NW area of 91 nodes. All transformers are equipped with off-load tap changers which are normally set at tap position 3.

Solar Irradiation and Load Profile Data

To simulate the variability of PV generation, actual solar irradiation data with 1-hour sampling rate during summer time is used. The data is measured at the NW area by The Royal Netherlands Meteorological Institute (KNMI) [12]. Specifically, the global horizontal irradiance (in W/m^2) with the 24-hour measurement in a week from 2-8 July 2018 is chosen, as shown in Figure 4. In Vision Network Analysis, this profile is applied to both PV inverters regarding per unit (p.u.) scale, with one p.u. is 1000 W/m^2.

Five different load profiles are applied to the test network based on the load profiles standard in the Netherlands as shown in Figure 5 [13]. These load profiles are then allocated to 91 active nodes in the test network.

Proposed Sequential Control Approach

The sequential control of *Q* - *V* droop-based RPA and *P* - *V* droop-based APC of the PV inverters introduced in [7] is adopted in this work. The controlling purposes consist of maintaining the voltage at the primary side (V_{prim}) and secondary side (V_{sec}) of the transformers within the acceptable range, maximize $P_{injected}$ of PV system, avoiding

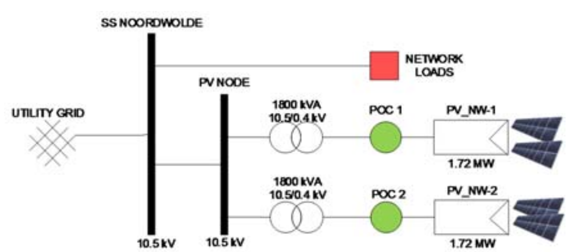

Figure 2. New PV systems connected to NW substation.

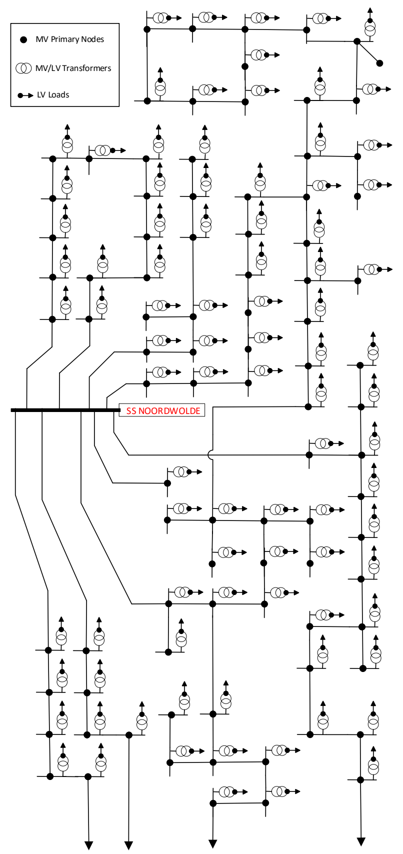

Figure 3. Simulation test NW distribution network.

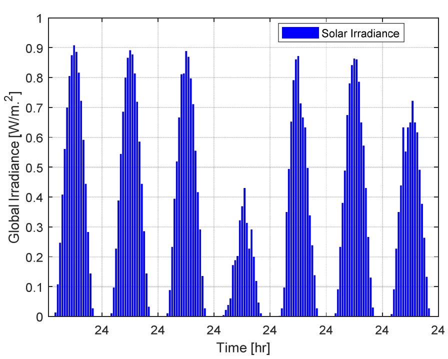

Figure 4. Solar irradiation profile used in the simulation.

overloading of transformers connecting to PV system (L_{trafo}), and minimizing the average power losses per hour (P_{losses}) of the network. With V_{thQ} being smaller than V_{thP}, RPA is activated first to solve voltage rise problems, then APC will active if voltage keeps increasing.

RESULTS AND DISCUSSION

Simulation is performed in Vision Network Analysis with four control cases for a week. Case 1 applies no any control of the PV inverters in response to voltage violation problems. Case 2 utilizes APC to mitigate the voltage rise issues, while Case 3 utilizes RPA. In case 4, the proposed

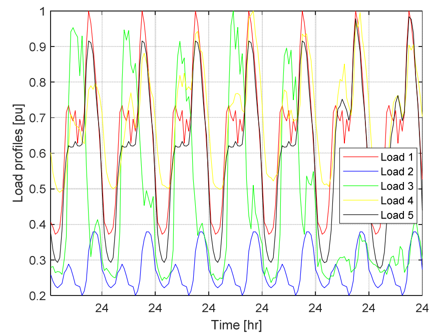

Figure 5. Load profiles used in the simulation.

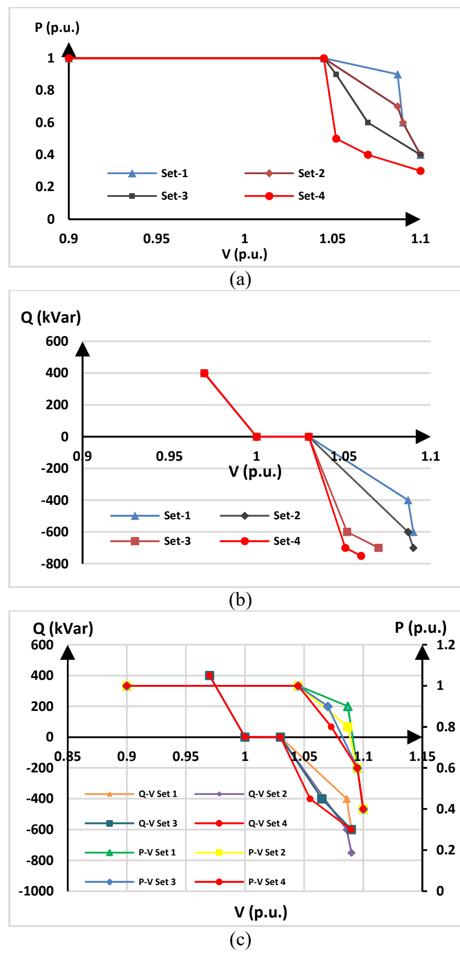

Figure 6. Controller settings for APC (a), RPA (b), and sequential RPA-APC control (c).

sequential RPA-APC control scheme is implemented. To investigate the sensitivity of the control parameters in Case 2, 3 and 4, four different settings are applied as shown in Figure 6. These settings vary from less aggressive to more aggressive in terms of voltage threshold values and amount of curtailed active power and absorbed reactive power.

Case 1: No control employment

Without any control, the results reveal the impact of large-

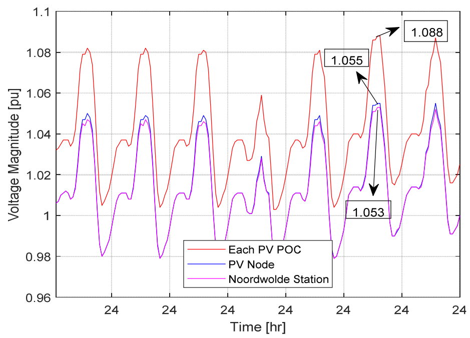

Figure 7. Voltage levels at POC, PV Node, and NW substation.

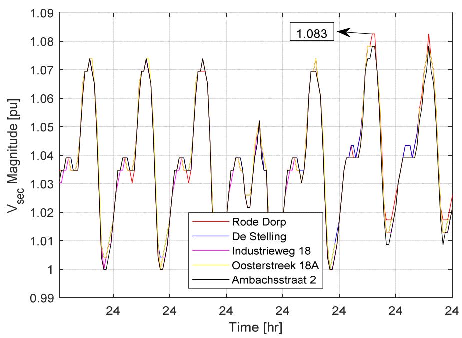

Figure 8. Secondary voltage levels of five feeders directly connected to NW substation.

scale PV integration on the voltage violation problem in NW network. From Figure 7, it can be observed that the highest values of V_{POC}, voltage at PV node (V_{PV}), and V_{prim} are 1.088 p.u., 1.055 p.u., and 1.053 p.u., respectively. Additionally, the increasing V_{prim} lead to increasing V_{sec}. Figure 8 indicates the voltage profile of V_{sec} measured at five feeders directly connected to NW substation. The average voltage level is around 1.07 p.u., while the highest value is 1.083 p.u. occurring in Rode Dorp feeder.

Case 2: APC Method

The first voltage rise mitigation is conducted by implementing the APC method. The controlling purpose is to regulate V_{prim} in the NW network lower than 1.03 p.u. and V_{sec} lower than 1.05 p.u. The simulation results are shown in Table 1 and Figure 9. Setting 4 with aggressive active power curtailment guarantees the achievement of the desired values of V_{prim} and V_{sec}. Nevertheless, as shown in Figure 9, this method curtails a high amount of active power generation with active power injection being only 45% of the rate capacity of the PV inverters. Hence, this method is less considered to be implemented.

Case 3: RPA Method

The desired voltage levels are set with the same values in Case 2. The setting of Q_{max} of PV inverter is of 0.75MVAr. Table 2 summarizes the results of RPA method. The setting 3 and 4 which are the most aggressive ones with the utilization of Q_{max} are only able to achieve the desired value of V_{prim}. $P_{injected}$ of the PV system is regulated at the maximum value. Notwithstanding, this RPA method causes the overloading of the transformers with L_{trafo} of 106% due to the presence of reactive power in addition to active power flow. The power losses of the network, P_{losses} also increase with more reactive power flow in the network. These drawbacks must be taken into consideration by the network operators if they choose to implement this method.

Properties	Set 1	Set 2	Set 3	Set 4
Max V_{prim} (p.u.)	1.052	1.044	1.032	1.025
Max V_{sec} (p.u.)	1.083	1.074	1.06	1.05
$P_{injected}$ (MW)	3.44	3.182	2.268	1.556
P_{losses} (MW)	0.092	0.087	0.081	0.080
L_{trafo} (%)	100	93	66	40

Table 1. Results of APC method.

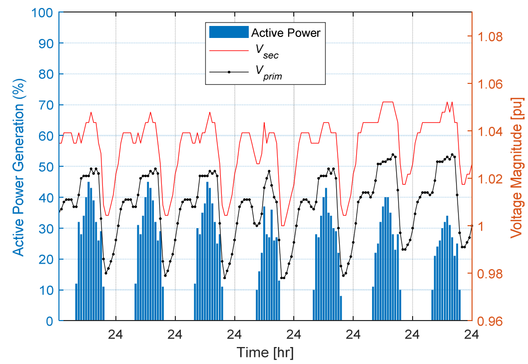

Figure 9. Active power and voltage levels with APC method.

Properties	Set 1	Set 2	Set 3	Set 4
Max V_{prim} (p.u.)	1.039	1.033	1.03	1.029
Max V_{sec} (p.u.)	1.07	1.06	1.06	1.056
$P_{injected}$ (MW)	3.44	3.44	3.44	3.44
P_{losses} (MW)	0.095	0.098	0.104	0.106
L_{trafo} (%)	99	103	105	106

Table 2. Results for RPA method.

Case 4: Proposed sequential RPA-APC control

The results of the sequential RPA-APC control are summarized in Table 3. It illustrates that this sequential control is able to guarantee the achievement of the desired voltage levels of V_{prim} and V_{sec}, while maintaining the maximum $P_{injected}$ of PV system and also minimum P_{losses} of the test network. Table 4 shows the details of setting 3, in which V_{thQ} is of 1.065 p.u. and V_{thP} is of 1.07 p.u., implying that RPA will be triggered prior to APC. Figure 10 displays active power generation and voltage levels stemming from the sequential RPA-APC control running for a week. $P_{injected}$ of PV system reaches up to 97% of the rated capacity, while V_{prim} and V_{sec} are ensured within the desired range.

Properties	Set 1	Set 2	Set 3	Set 4
Max V_{prim} (p.u.)	1.039	1.029	1.027	1.025
Max V_{sec} (p.u.)	1.07	1.06	1.05	1.05
$P_{injected}$ (MW)	3.44	3.44	3.322	3.13
P_{losses} (MW)	0.094	0.094	0.092	0.090
L_{trafo} (%)	100	101	97	93

Table 3. Results for sequential RPA-APC control.

V (p.u.)	1.03	1.045	1.065	1.07	1.09	1.095
Q (MVar)	0		-0.4		-0.6	
P (p.u.)		1		0.9		0.6

Table 4. Setting 3 for sequential RPA-APC control.

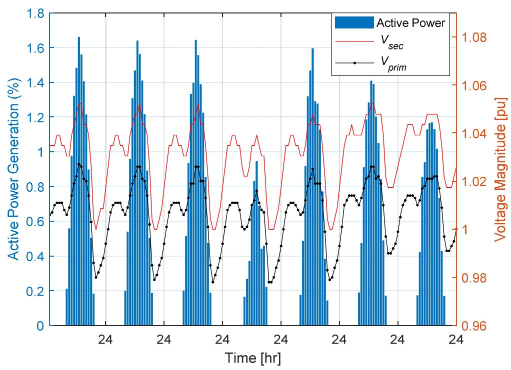

Figure 10. Active power and voltage levels with RPA-APC.

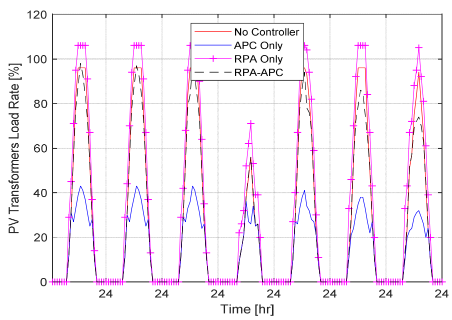

Figure 11. Comparison of load rate of transformer connecting to PV.

Properties	Case 1	Case 2	Case 3	Case 4
Max V_{prim} (p.u.)	1.053	1.025	1.029	1.027
Max V_{sec} (p.u.)	1.083	1.05	1.056	1.05
$P_{injected}$ (MW)	3.44	1.556	3.44	3.32
P_{losses} (MW)	0.094	0.080	0.106	0.092
L_{trafo} (%)	96	40	106	97

Table 5. Summarized main results.

Key results of four control cases are compared in Figure 11 and Table 5. Figure 11 indicates that applying the sequential RPA-APC control results in no overloading of the coupling transformers. From Table 5, it is evident that the proposed sequential control is the most effective approach to regulate the voltage levels V_{prim} and V_{sec}, prevent overloading of transformers connecting to PV system (L_{trafo}), and minimize the power losses (P_{losses}) of the network.

CONCLUSION

This paper investigates the voltage rise problems arised from the integration of a large-scale PV system into a distribution network in Noordwolde, the Netherlands. The sequential RPA-APC control method is subsequently proposed to mitigate such problem. This sequential control is implemented by the PV inverters utilizing *Q-V* droop control prior to *P-V* droop control. Simulation is performed in Vision Network Analysis with actual data measured at the field. Analysis of simulation results of the proposed control scheme is implemented through the comparison with different control cases. The proposed control can help network operators in solving the voltage rise problem while also help PV owners in minimizing the loss of energy in response to the voltage rise problem. Further research can be conducted to develop an algorithm to determine the voltage threshold values for RPA and APC control.

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