Voltage Management Challenges in Feeders with High Penetration of Distributed Generation

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***Abstract*—Interconnection of relatively large independent power producers (IPP) in distribution feeders has created new challenges for the system operators and planners. In this paper, issues pertaining to voltage management in the presence of multiple IPPs and voltage regulators are discussed based on years of utility experiences with high penetration of IPPs. A setpoint-free strategy is proposed for voltage regulators which combines the benefits of the conventional control modes. A reactive power control mode is also proposed for IPPs which ensures no interference in voltage regulation of the feeder when a voltage regulator is present. The proposed control strategies are tested for a variety of load/generation scenarios.**

***Index Terms*—Independent power producer, voltage management.**

I. INTRODUCTION

THE policies set by most governments for green energy initiatives encourage the concept of distributed generation, also known as independent power producers (IPP). The benefits of IPPs are twofold. An evident benefit is that IPPs may produce energy from renewable resources, such as hydro, solar, wind, biomass, etc, thus contributing to the reduction of environmental impacts of burning fossil fuels. The other benefit of IPPs is to avoid transmitting power over long distances with the corresponding associated losses by producing electrical energy in the vicinity of the demand centers. Despite these benefits, there are technical issues in the grid interconnection of IPPs at distribution feeders. A comprehensive analysis was done in [1] to review the pros and cons of installing IPPs.

Traditionally, distribution feeders were built for unidirectional power flow, starting from the substation down to all loads connected to the feeder. With this assumption, the voltage magnitude continuously drops along the feeder. Moreover, the control logic of under-load tap-changers (ULTC) and voltage regulators (VR) are based on uni-directional power flow. As soon as an IPP is connected to the feeder, these assumptions may be violated and need to be revised [2]. Of particular interest to the authors are the voltage management issues and coordination requirements for various volt-VAR equipment. There are two major streams in the literature to address this problem. The availability of a communication infrastructure is the main driver to choose a coordination methodology. When the communication platform is available, a centralized supervisory control (referred here to as "global control") is possible. Otherwise, the control logic should be based on a decentralized approach (referred here to as "local control").

A. Literature Review

1) Local Control Strategies: In [3], a strategy for choosing proper voltage setpoints for ULTC's with or without line drop compensation capability was proposed. It was shown that by proper coordination, even in the presence of IPPs, no major issues occur in terms of feeder voltage management. However, the possibility of hunting effects between IPPs and VRs was not considered. Appropriate setpoints for ULTC, SCs, and IPPs were derived in [4] based on a number of off-line simulations. A daily load curve was used as reference to perform the simulations. This control strategy, however, may not be valid for seasonal variations in load and/or generation since the setpoints were calculated based on a single day load curve. A voltage management strategy, together with a line thermal watchdog, was proposed in [5] to control the active and reactive power output of IPPs. The strategy is based on sensitivity factors derived using a snapshot power flow of the feeder. Practically speaking, this strategy requires communication between all the major points on a feeder to obtain accurate sensitivity factors at each snapshot power flow.

A Thévenin equivalent of the feeder was estimated from the point of interconnection (POI) in [6] and an optimization problem was solved locally to obtain a suitable voltage setpoint. This optimization problem aims at improving the voltage profile across the feeder by estimating the voltages at other nodes. This method has limited application since it may not work properly when multiple IPPs are present on the same feeder or when a VR exists upstream the IPP.

2) Global Control Strategies: A limited communication was assumed in [7] between adjacent equipment and each equipment estimates the state of other critical points based on a bio-inspired paradigm. The setpoints were then readjusted to satisfy some objective function. A gradient-based optimization needs to be solved by the sensor networks at every iteration which possibly finds a local optimum. A strategy was proposed in [8] to coordinate photovoltaic generation, ULTC, and static VAR compensators using a centralized optimization framework. The objective of this optimization problem is to minimize the energy losses and the number of discrete operations of control devices over a 24-hour period. This method assumes forecasts of load and generation for a day-ahead planning horizon, which introduces many uncertainties

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to the problem. Also, it requires the solution of a challenging optimization problem with discrete variables and nonlinear constraints.

A two-way communication based distributed control method was proposed in [9] for voltage control in distribution feeders. Some of the issues related to the penetration of distributed generation in feeders with a VR operating in line-drop compensation mode were studied. It was shown that the power injection from the DGs can impede the proper operation of the VR. An architecture was proposed in which every equipment performs a local control with a two-way communication with other equipment to ensure a proper voltage profile across the feeder. A Genetic Algorithm-based optimization was formulated in [10] that minimizes the power losses and improves the feeder voltage profile simultaneously. This method requires communication with a centralized controller, where all the decisions are made in real-time operation.

B. Proposed Strategies

There are benefits in using a centralized (global) control strategy for volt-VAR management in distribution systems. Some of the benefits in terms of voltage profile improvement, loss reduction, and demand reduction were discussed in [11]. However, this may not always be an option due to unavailability of proper communication infrastructure. In such cases, a local control strategy can be designed for each control equipment, so that no conflict occurs in any possible operating scenario. To this end, some of the possible voltage control issues in feeders with IPPs, VRs, SCs, and substation ULTC are described in this paper. These issues have been observed over a period of time by BC Hydro and deserve more attention. Some of these issues have been:

- An IPP is located downstream of a VR.
- Multiple IPPs are connected to the same feeder.
- The substation transformer is equipped with ULTC capability.

The contributions of this paper are as follows:

1) The operation challenges for voltage management in feeders with different volt-VAR control equipment are highlighted based on industry experience.
2) A setpoint-free voltage regulation scheme is proposed for voltage regulators which takes into account cases that may not be covered by commercially available schemes.
3) A reactive power control mode is proposed for distributed generators that eliminates some of the issues pertained to other available control modes.

II. CHALLENGES IN VOLTAGE MANAGEMENT WITH HIGH PENETRATION OF IPPS

A. Interactions Between an IPP and a VR

In order to highlight the issues pertaining to the simultaneous operation of an IPP and a VR, a simple distribution feeder is used here. This feeder is a 105 km long, 25 kV overhead line with loads scattered all over the feeder. Each load is rated at $1 + j0.1$ MVA, representing the sum of all the loads on that particular feeder section. A VR is located 45 km downstream the substation and an IPP, rated at 10 MVA, is connected to the end of the feeder. The IPP consists of synchronous generator units, driven by run-of-river turbines. An overview of this feeder is shown in Fig. 1.

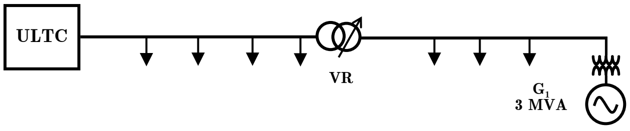


Figure 1. A radial feeder with a voltage regulator and an IPP.

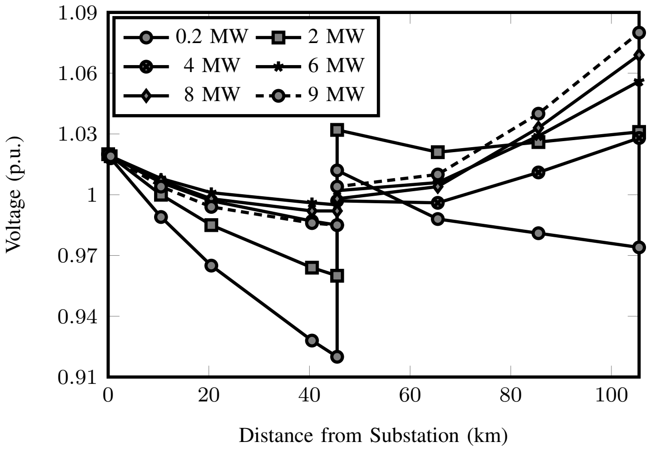
Two cases are studied: 1) IPP is operated in voltage control mode (VCM); 2) IPP is operated in power factor control mode (PFCM). In both cases, the VR is operated in co-generation mode. In this mode, different setpoints can be defined for “Forward” and “Reverse” power flows. To ensure the end-of-line voltage is above the minimum limit in light generation cases, a setpoint of 1.033 p.u. is chosen for the Forward mode. Similarly, to ensure the end-of-line voltage is below the maximum limit for high generation, a setpoint of 1.0 p.u. is chosen for the Reverse mode. For the same load profile, the output of the IPP is increased from 0.2 MW up to 9 MW. The voltage setpoint for the IPP is set to 1.022 p.u. for the VCM case. The voltage profile of this feeder for the two cases is shown in Fig. 2.

When the IPP is operated in PFCM (Fig. 2(a)), the voltage at the end of the line exceeds the maximum limit during high generation. On the other hand, the voltage at the node right before the VR drops below the minimum limit during low generation. When the IPP is operated in VCM (Fig. 2(b)), the voltage at the node right before the VR drops below the minimum limit during high generation. This happens because of the excessive reactive power drawn by the IPP to keep the voltage down. One important issue regarding most of the IPPs connected to the BC Hydro system, mainly run-of-river salient-pole synchronous machines, is the impact of under-excitation on the machine and its performance. When the machine is under-excited, the field current is small and the flux created by the armature current is added up to the flux produced by the field current. This situation escalates the end-core localized heating in the machine windings. This practical limit should be considered to avoid an under-excited machine.

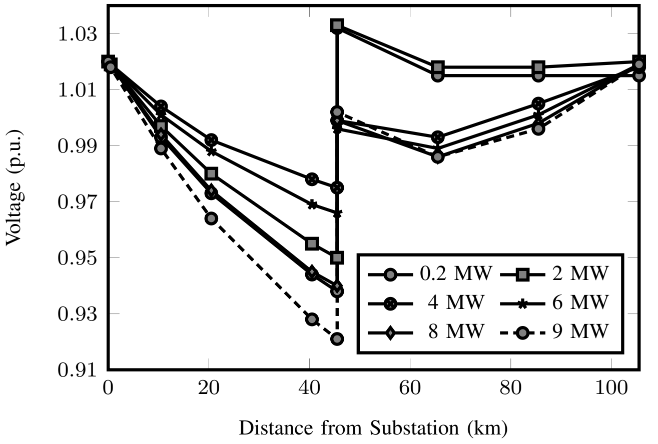
When a VR is operated in the co-generation mode, choosing the two setpoints far from each other causes unnecessary tap operations if fluctuations happen around the threshold defined for Forward/Reverse modes. Choosing equal values for the setpoints is also not a good option since it causes over/under voltage problems in Reverse/Forward power flows.

B. Interactions Between Multiple IPPs

When more than one IPP are connected to the same feeder and they are operated in VCM, there is a chance that, due to poor coordination, large amount of reactive power is exchanged between the units. To understand this problem, consider the feeder shown in Fig. 3. This feeder is similar to the one shown in Fig. 1 with the only difference that there



(a) IPP in PFCM



(b) IPP in VCM

Figure 2. Feeder voltage profile for different generation levels and control modes.

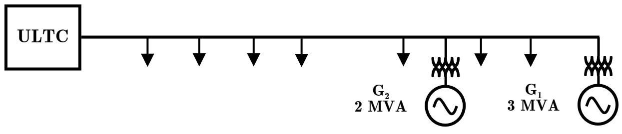


Figure 3. A radial feeder with two IPPs.

Table I
Impact of Voltage Setpoint on Reactive Power Generation for Multiple IPPs

		Case1	Case2	Case3	Case4
V Setpoint (p.u.)	G_1	1.02	1.02	1.04	1.01
	G_2	1.04	1.02	1.02	1.00
Q (MVAR)	G_1	-0.77	-0.30	0.37	0
	G_2	1.60	0.69	0.14	0

are two IPPs connected to it. The VR is set to neutral (fixed-tap) for this case to specifically see the interaction between the IPPs. An example of uncoordinated voltage setpoint for these generators is as follows: 1.02 for G_1 and 1.04 for G_2. Using these settings, assuming G_1 generates 2 MW and G_2 generates 1 MW, 1.6 MVAR reactive power is generated by G_2 and 0.77 MVAR is absorbed by G_1. This excessive reactive power flow creates losses in the network and deteriorates the excitation system of the synchronous machines. Other cases can also be considered for voltage setpoints, assuming the same active power generation, as shown in Table I. A try-and-error shows that the settings in Case 4 minimize the reactive power exchange while maintaining a good voltage profile for this particular load/generation scenario. In reality, due to the continuous change in load and generation on the feeder, it is not possible to find a setpoint for these generators that ensures an optimal operation in all the possible scenarios. For this reason, the IPPs should be operated in PFCM to avoid any conflict in voltage control between them. If voltage support is required, only one IPP should operate in VCM and the rest in PFCM. If a VR is present, however, the issues stated in Section II-A may arise.

C. Interactions Between IPPs and Substation ULTC

The step-down transformer at a substation is usually equipped with an under-load tap changer (ULTC). This allows for regulating the voltage at the substation when there is a change in the voltage at the HV/MV network. This ULTC usually operates with a delay that ranges from 30 s to 60 s. When there is an IPP connected to a feeder and is operated in VCM, any changes in the voltage of the HV/MV system is immediately seen by its AVR. In this case, the IPP reacts to the voltage change before the ULTC. For example, a 0.5% voltage rise at the HV/MV side of the substation transformer causes an immediate 0.5% voltage rise at the IPP terminal. More reactive power is absorbed by the IPP. This situation causes a large amount of reactive power to be drawn from the HV/MV network which, in turn, creates extra losses in both distribution feeder and HV/MV network. This is also an interference with the expected functionality of an ULTC to regulate the voltage.

The above situation will end when the machine hits the excitation limit and if the voltage continues to rise, then the ULTC will eventually respond and reduce the voltage. A change in an adjacent feeder could also cause a similar problem.

III. Proposed Volt-VAR Control Strategies

Several issues were discussed in Section II regarding voltage control when IPPs are connected to a feeder. In this section, control strategies are proposed for VRs and IPPs to reduce their impact on the voltage profile and avoid any possible conflict in voltage control.

A. Setpoint-Free Voltage Regulation

The control options available in a commercial VR include No Reverse, Reverse Idle, Neutral Idle, Locked Forward, Locked Reverse, Bi-Directional, Reactive Bi-Directional, and Co-Generation modes. These modes are explained in [12]. All these modes require a predefined voltage setpoint. Due to the dynamic nature of load and generation, these setpoints are not suitable for the entire year and compromises have to be made. Instead of setting the voltage to a fixed value at a fixed node in

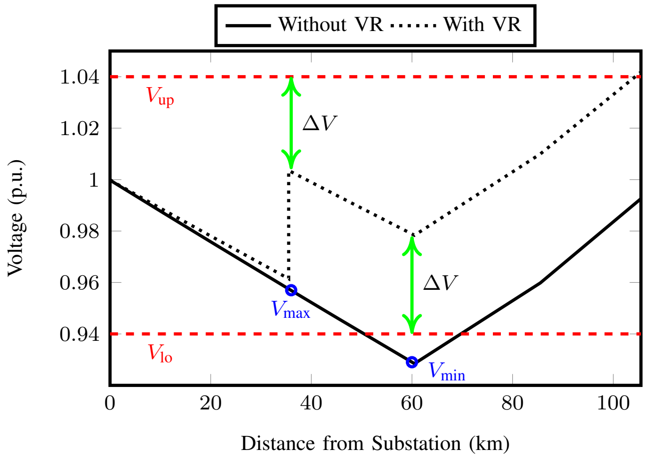


Figure 4. Feeder voltage profile when the IPP generates 7 MW at unity power factor and VR uses the setpoint-free algorithm.

the feeder, the authors propose to set the voltage for a broader section of the feeder.

Similar to the concept of protection zones for protective relays, a "regulation zone" can be defined for a VR. A regulation zone is the longest path on the feeder downstream a VR in which there is no voltage/VAR control equipment (e.g., capacitor, IPP, VR, etc.) and no significant load (or aggregation of loads) that may cause a voltage change greater than 1%. This definition of regulation zone ensures that the voltage in this zone is mainly controlled by the VR. This can be introduced to the VR controller as an equivalent impedance. This idea is similar to the Line-Drop Compensation adopted by the commercial VRs and ULTCs [12]. However, instead of introducing a fixed voltage setpoint for the load center, the authors propose to automatically choose the setpoint, depending on the active and reactive power flow through the regulation zone.

Without IPPs, the voltage profile usually resembles a declining line for a radial feeder, starting from the substation to the end of the feeder. With significant penetration of IPPs, however, multiple cases may occur. One of the interesting cases is when a low-voltage point appears between the IPP and the substation. Consider the feeder shown in Fig. 1 without the VR and the IPP in PFCM, generating 7 MW. Some loads are relocated (same total) so that from 30 km up to 60 km of the feeder, there is no significant load. The feeder voltage profile for this case is shown in Fig. 4. As can be seen, the voltage starts to drop downstream the substation up to 60 km. Beyond this point, voltages rise all the way to the end of the feeder, where the IPP is connected. This happens primarily due to a large amount of reactive power (2.2 MVAR in this case) traveling from the substation into the feeder. Assume a VR is located 35 km away from the substation. If the VR controls only its terminal voltage, it will miss the voltage drop ahead. On the other hand, if the VR controls the voltage at a point, for example, 80 km away from the substation (line-drop compensation mode), it will again miss the low-voltage point in the middle.

The issue with the co-generation mode, available from some manufacturers, is that if the power fluctuates between the thresholds, and if there is a large difference between the Forward and Reverse settings, multiple tap operations may happen frequently.

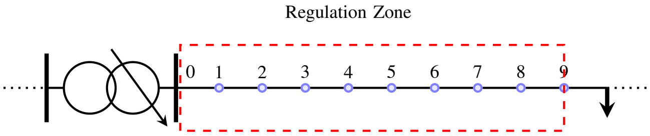


Figure 5. Voltage regulation zone.

Assume a voltage regulation zone is established, for example, between 35 km and 60 km on the feeder of Fig. 4. The proposed control methodology is to balance the voltage margins from the lower and upper voltage limits (V_{lo} and V_{up}) in the regulation zone. For example, the two ΔV's shown in Fig. 4 should be equal. The values of V_{lo} and V_{up} can be defined by the operator. To ensure appropriate settings, a study for minimum load-maximum generation and maximum load-minimum generation scenarios should be conducted.

To estimate the voltage profile within the regulation zone, assuming that the active power (P), reactive power (Q), and voltage (V_0) can be measured at the VR location, the following formula can be used:

$$V_i = \sqrt{(V_0 - R_i P - X_i Q)^2 + (X_i P - R_i Q)^2} \qquad (1)$$

in which R_i and X_i are the equivalent resistance and reactance of i^{th} point within the regulation zone, respectively. A total of n points, equally spaced, are evaluated within the regulation zone and an estimation of the voltage profile in this zone is created. Figure 5 shows the regulation zone and the hypothetical points in the zone for voltage evaluation. Note that the above formula may not reconstruct the exact voltage profile due to small loads that might be present in the regulation zone. Once the estimation process is done, the minimum and maximum voltages, V_{min} and V_{max}, are determined within the regulation zone. An appropriate buck/boost level is then determined that balances the available voltage margins $|V_{\text{max}} - V_{\text{up}}|$ and $|V_{\text{min}} - V_{\text{lo}}|$ (See Fig. 4). This method basically places the voltage profile of the regulation zone at a balanced distance from the upper and lower limits.

B. Generator Reactive Power Control

As discussed in Section II, none of the VCM and PFCM are ideal options for controlling IPPs when a VR is present. An ideal case would be to operate the IPP in such a way that it does not interfere with the VR, while providing appropriate VAR support. The proposed strategy is to keep the point of interconnection (POI) a floating voltage point, i.e. the POI follows the voltage dictated by the VR. In order to achieve this, a look-up table is created that gives appropriate values of reactive power exchange for every value of active power generation, as described in the following. This is referred to as reactive power control mode (QCM).

Consider the feeder shown in Fig. 1. The VR is set to the neutral tap position. If this creates voltages below the minimum limit, then the tap is set at a level that creates the minimum allowable voltage at the POI. The output power of the IPP is varied from zero to the maximum and its terminal voltage is recorded. At every step, the appropriate reactive power exchange is determined that keeps the voltage at a desired level, considering the reactive limits of the generator. Sometimes, it is desired to have some reactive power support from the IPP for load power factor correction. In such cases, an offset is added to the reactive power column of the look-up table in the low-generation scenarios.

There are cases when the voltage may go beyond the standard limits at the POI. This situation may happen due to a malfunction of the VR, high generation, heavy load, etc. As soon as the voltage exceeds the predefined limits at the POI, the generator is switched to VCM to keep the voltage within the limits. When the situation is back to normal, the AVR switches back to QCM.

The proposed strategy makes the POI a floating point that follows the voltage regulated by the VR. In other words, there is no interference in voltage regulation between the VR and the IPP. The generator reactive power is a function of its active power output, not the terminal voltage.

IV. SIMULATION RESULTS

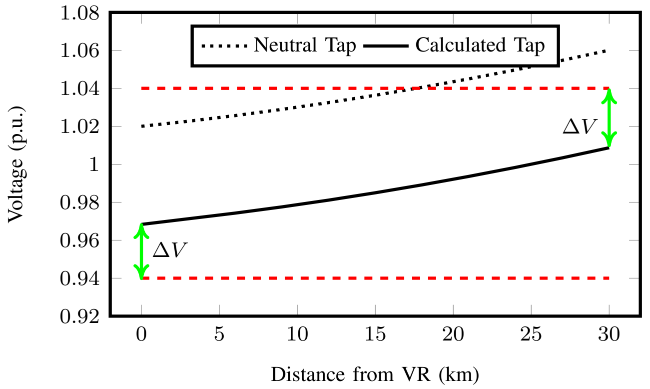
A. Setpoint-Free Voltage Regulator Control

Consider the VR and its regulation zone shown in Fig. 5. The value of active and reactive power flowing through the VR determine the shape of the voltage profile. Figure 6 shows the possible scenarios. When power flows in the reverse direction, the voltage rises downstream the VR (Fig. 6(a)). When power flows in the forward direction, the voltage drops downstream the VR (Fig. 6(b)). When there is a large amount of power flowing in the reverse direction while a large amount of reactive power flows in the forward direction, as shown in Fig. 6(c), a low-voltage point appears within the regulation zone. There are several cases in the BC Hydro distribution system that face such issues.

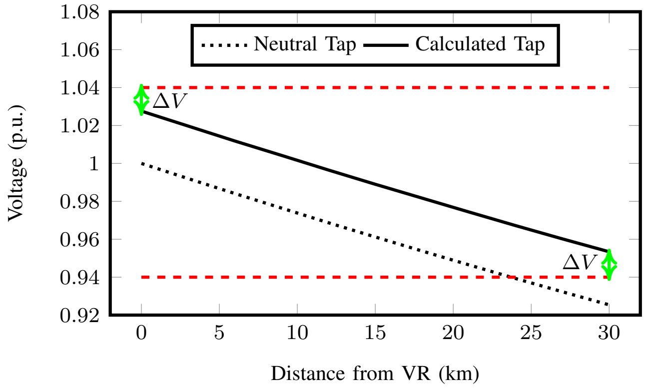
B. Generator Reactive Power Control Mode

The proposed reactive power control strategy is meant to minimize the interference of IPPs in voltage control of the feeder in the presence of voltage regulators. Simulation results were given for the feeder shown in Fig. 1 in Section II-A, when the IPP is operated in VCM and PFCM. The results presented in Fig. 2 demonstrated the inadequacy of the two conventional control strategies when interacting with a VR in co-generation mode.

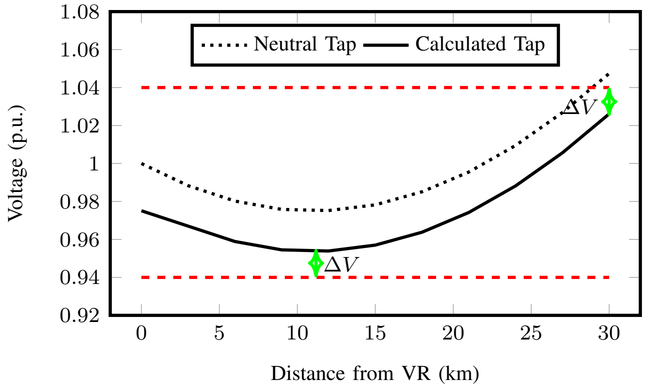
The proposed QCM method is applied to the same feeder shown in Fig. 1. First, a number of generation scenarios were run, considering a fixed tap position for the regulator. The tap position is chosen to be at the neutral. If the neutral position creates an out-of-limit voltage at the end of the feeder, then a tap position that creates the minimum voltage limit is chosen. The output of the IPP is increased in steps and for each step an appropriate value for the POI voltage is selected (V_g). This study is conducted for the peak load and the power flow direction through the VR is monitored as the IPP's output is increased. When the power direction is reversed, the tap position is moved to a position that produces the Reverse voltage setting, 1.00 p.u. in this example. The voltage at the POI for high generation scenarios is chosen to be high in order to avoid reactive power absorption by the IPP. Since the voltage drops as one moves towards the substation from the POI, keeping the voltage close to the upper limit insures that the voltages all over the feeder are kept within the limits while minimizing the reactive power flow.



(a) $P = -8$ MW, $Q = 3$ MVAR, $X = 0.3920\Omega/km$, $R = 0.2136\Omega/km$



(b) $P = 6$ MW, $Q = 1$ MVAR, $X = 0.3920\Omega/km$, $R = 0.2136\Omega/km$



(c) $P = -18$MW, $Q = 10$MVAR, $X = 0.5880\Omega/km$, $R = 0.1709\Omega/km$

Figure 6. Voltage profile in the regulation zone of a VR for different power flow scenarios.

The voltage profile of the network using the proposed QCM for the IPP and co-generation mode for the VR is shown in Fig. 7. In this figure, the active power generation of the IPP is

Table II
LOOK-UP TABLE PREPARED OFF-LINE FOR THE GENERATOR IN THE REACTIVE POWER CONTROL MODE

P (MW)	V_g (p.u.)	Flow at VR	PF (%)
0.2	0.99	Forward	30
1.0	1.00	Forward	95
2.0	1.02	Forward	100
3.0	1.04	Forward	-99.9
4.0	1.03	Reverse	100
5.0	1.03	Reverse	-99.9
6.0	1.04	Reverse	-99.95
7.0	1.04	Reverse	-99.63
8.0	1.04	Reverse	-99.68
9.0	1.04	Reverse	-99.57

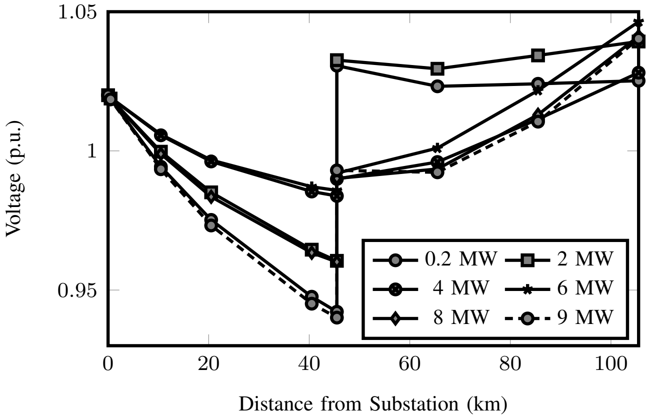


Figure 7. Feeder voltage profile for different generation levels when the IPP is in QCM (Total load is fixed at 7 MW).

increased in steps while the feeder load is kept constant at 7 MW. The look-up table in Table II can be calculated in finer steps for P and power factor and interpolation can be done for real-time application. As can be seen in Fig. 7, the feeder voltage profile falls within the limits for the peak load and variable generation.

The proposed QCM is also tested for a typical generation scenario of 5 MW and a variable feeder load. The results are shown in Fig. 8. It is important to note that the POI is a floating point, going up and down as the VR changes tap positions to regulate the voltage profile. In other words, the main job of voltage regulation is left to the VR and the IPP does not interfere with the VR's task.

V. CONCLUSION

A number of cases were studied in this paper to show the interaction between IPPs and VRs. When there are only two control options for an IPP, namely VCM and PFCM, and the VR is operated in co-generation mode, the following practices are recommended:

- An IPP is located downstream of a VR: The IPP should be operated in PFCM.
- Multiple IPPs are connected to the same feeder downstream of a VR: All IPPs should be operated in PFCM.

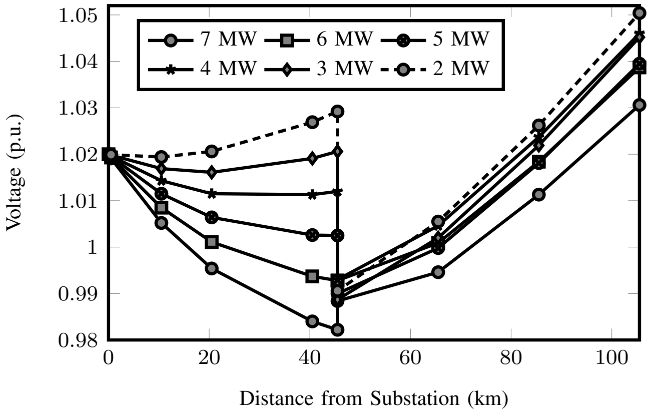


Figure 8. Feeder voltage profile for different load levels when the IPP is in QCM (Generation is fixed at 5 MW).

- Multiple IPPs are connected to the same feeder without a VR or upstream a VR: The largest IPP should be operated in VCM and the rest in PFCM.

Where user-defined programming is possible in the VR, the proposed setpoint-free voltage control strategy is recommended. Where additional programming options are available in the AVR system, the proposed QCM is recommended for a large IPP located downstream of a VR.

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