Economic Evaluation of PV Generation Curtailment and Voltage Regulation Investment in Distribution Networks with High PV Penetration

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Abstract. The continuing increase of photovoltaic (PV) generation in distribution systems comes with difficulties in keeping voltages within acceptable limits, especially during peak generation. Two conventional alternatives exist to solve these overvoltage issues: to install voltage regulation equipment (AVR) or curtail PV generation, but there is no existing procedure to aid distribution system operators (DSO) in choosing either solution from an economical perspective. This project presents a methodology to evaluate the two aforementioned alternatives. The equivalent annual cost of installing automatic voltage regulator systems in the network was compared to the annual compensation awarded to curtailed PV generator owners. Several case studies were explored and show that in some situations, curtailment can be more cost-effective depending on the curtailment compensation scheme used, amount of PV penetration, location of PV in the network, and demand profiles. Additionally, the researchers explored the economic viability of using curtailment in conjunction with existing AVR installations instead of installing additional AVRs.

Keywords: Photovoltaics · Renewable generation · Distribution networks · Voltage regulators · Curtailment

1 Introduction

In a move towards a future independent of fossil fuels, countries worldwide have adopted renewable energy systems. The use of renewable resources in distribution networks is steadily increasing, especially photovoltaic (PV) systems. It is predicted to further increase in the future because of the incentives provided by governments to prosumers and the adverse impacts of using conventional sources of power generation in the environment. The increase in connected renewable resources comes with its drawbacks. It may threaten the power quality in

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distribution networks and cause issues like voltage swell and voltage sag. These can cause detrimental effects on existing protection schemes and increase wear on utility equipment [1].

Voltage level is one of the crucial parameters of the grid that a distribution system operator (DSO) must always maintain within limits so that the load side of the network will have an acceptable range of voltage supply. An option for DSOs is to invest in additional voltage regulation equipment to maintain voltages within these required limits. Traditionally, DSOs upgrade their networks by adding conventional on-load tap changer transformers (OLTC) coupled with automatic voltage regulator (AVR) relays to regulate transformer output voltages within the set voltage limits [2]. The OLTC is an automatic relay-controlled transformer component where it changes the voltage at the system using the tap settings of transformers [3]. Meanwhile, the AVR determines the load-side voltages and currents of the transformer, and eventually differentiates the measured voltage and reference voltage. If the difference surpasses the AVR's tolerance setting, then the tap setting will be automatically adjusted to normalize the transformer voltage at load side [4]. The AVR relay helps to control the local or remotely-located voltages in the system to keep them within set limits [5].

Since installing voltage regulation equipment may require a considerable investment in time and money for DSOs, an alternative is to curtail the output of generation. Curtailment today typically occurs because of constraints in the network or as a precaution against a foreseen instability in the system. However, curtailing renewable generation is seen negatively by the general public as "green" energy is lost. Generation from renewable sources has nearly zero marginal costs and so, it can be an economic loss as well. That said, curtailment can be a viable solution to problems when integrating this generation into the grid. Full integration of all generation can lead to excessive investment in equipment upgrades, infrastructure extension and deter further investment into renewable generation.

There are four main categories of curtailment situations, which can be both voluntary and involuntary: (1) network constraints, (2) security, (3) excess generation and (4) strategic bidding. Curtailment for security, excess generation, and strategic bidding is mainly used with the goal of minimizing market-related costs. For network constraints, the goal is to avoid over-investment in capacity and/or to delay investing in increasing capacity. It is suggested that compensation, in the case of network constraints or network extension delays, can be shouldered by the DSO using market prices or a fraction thereof [6].

A DSO is concerned not only with keeping system operations stable but also economical, so some cost analysis and comparison is required when considering if delaying network upgrades through curtailment is still profitable. Currently, no procedure or platform exists to make it easier for the DSO to choose between curtailment or investment in voltage regulation equipment.

This paper presents a procedure to assist DSOs in the economic evaluation of two alternatives to solve overvoltage problems caused by high PV penetration in their networks: (1) installing voltage regulation equipment or (2) curtailment of

PV generation. In particular, the equivalent annual cost for voltage regulation installation will be compared to the total annual compensation to generator owners.

2 Methodology

To build the test system, data regarding load and generation profiles and cost analysis were acquired. After building the base test system, a baseline scenario was applied and simulated. Using the results of the baseline scenario, economic analysis for the AVR installation and curtailment was performed. Lastly, several case studies were observed.

2.1 Test System Building

Building the test system required hourly residential and commercial load profiles, as well as hourly irradiation data which were acquired from [7,8] respectively.

The IEEE 34 node test feeder without AVRs was used for the test network. The IEEE 34-bus system is a standard test network that was designed to evaluate and benchmark algorithms in solving unbalanced radial distribution systems, and is also suited for use in systems with distributed generation. This test network is an actual radial distribution feeder operating at 60 Hz, 24.9 kV and 12 MVA, depicted in Fig. 1. In order to manage the undervoltage in the system at peak load, specifically at bus 890, the capacitor bank is removed, and the spot load at bus 890 is decreased.

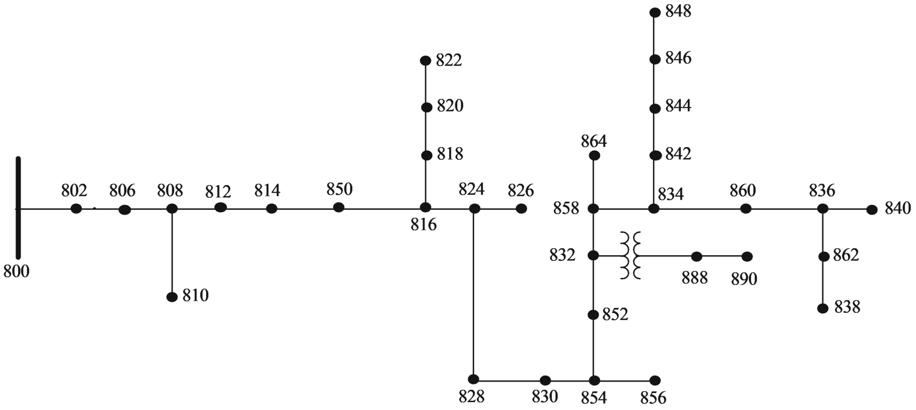


Fig. 1. Modified IEEE 34-bus system

Each PV system connected to the network is modeled as a 60 kW capacity generator operating at unity power factor.

The power flow is conducted using the EPRI distribution simulation tool, OpenDSS. OpenDSS is used for its full multiphase model, built-in IEEE 34 feeder test case code, and relatively easy data exchange interface with MATLAB.

2.2 Optimal AVR Positioning

The method in [9] is used for the initial placement of AVR in the test system based on technical criteria. The method is started by using load flow to compute the bus voltages. From the results of the load flow, critical paths are identified. A critical path is the path from a bus with the highest overvoltage to the substation. In each critical path, an AVR is positioned at the end node. After that, a load flow is run to check the overvoltage in the system. Then, an objective function considering technical aspects, the voltage drop percentual factor $F_{at_v}\%$, is computed using the configuration. The $F_{at_v}\%$ is used to show the quality of a certain placement of AVR in terms of voltages, shown in 1. Next, the AVR is moved upstream to the next bus of the critical path and the steps are repeated until the substation bus is reached. The AVR is positioned at the bus which produced the smallest $F_{at_v}\%$ and did not contain overvoltages throughout the system. The method is tested using the load and PV generation data of the average hour in the month where the highest overvoltage for the whole year occurred, which in this case is at hour 13 of May. A flowchart of the algorithm is presented in Fig. 2.

$$F_{at_v}\% = \frac{\sum_{i=1}^{N}\left(V_{nom} - v_i^f\right)^2}{\sum_{i=1}^{N}\left(V_{nom} - v_i^0\right)^2} \cdot 100 \tag{1}$$

where $F_{at_v}\%$ is the voltage drop percentual factor, V_{nom} is the upper voltage limit, and v_i^f and v_i^0 are the hourly instantaneous voltages measured with and without AVR installed at bus i, respectively.

2.3 Curtailment OPF

The curtailment optimal power flow (OPF) still utilizes the OpenDSS power flow with the addition of the following constraints:

$$0 \leq P_{gi} \leq P_{gi}^{max} \tag{2}$$

$$0.9pu \leq v_i \leq 1.10pu \tag{3}$$

where P_{gi} is the active power generation dispatched at bus i for the specified hour, P_{gi}^{max} is the maximum active power generation for bus i and v_i is the instantaneous voltage measured at bus i for the specified hour.

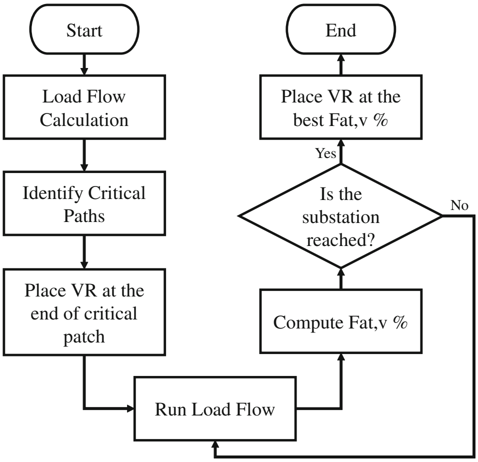


Fig. 2. AVR positioning method

Curtailment priority is modeled as an optimal dispatch problem, shown in 4, with a linear cost function Ω_{gi} shown in 5.

$$min\left(\sum_{i=1}^{N}\Omega_{gi}\left(P_{gi}\right)+\sum_{i=1}^{N}W_i\right) \tag{4}$$

$$\Omega_{gi}\left(P_{gi}\right)=P_{gi}^{max}-P_{gi} \tag{5}$$

$$W_i=\begin{cases}S_i\left(v_i-V_{max}\right)^2 & V_{max}\\ S_i\left(v_i-V_{min}\right)^2 & V_{min}\end{cases} \tag{6}$$

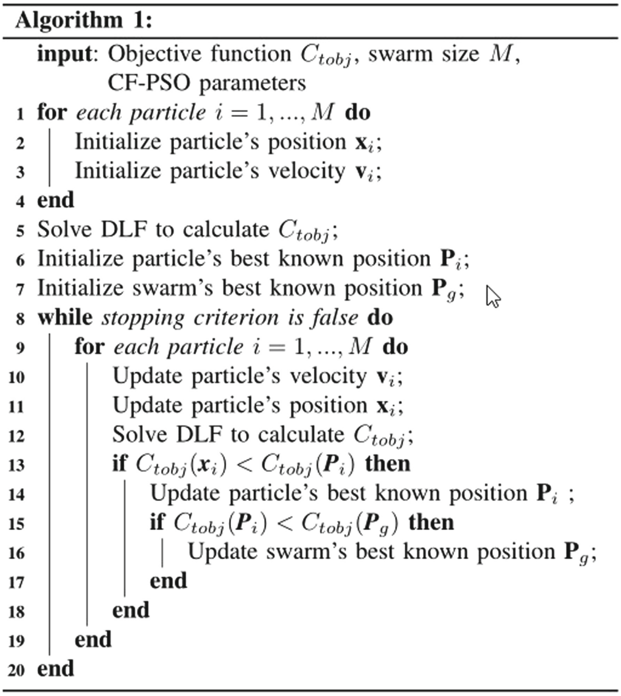
The constrained optimization problem is expressed as an unconstrained optimization problem by expressing the voltage constraint 3 as a penalty function W_i, shown in 6. S_i is the penalty factor which is set at an arbitrarily large number. V_{min} and V_{max} are the lower and upper voltage limits, respectively.

Constriction Factor Particle Swarm Optimization (CF-PSO) is then used for the optimization, described in [10]. The CF-PSO algorithm is initialized by generating a random population, referred to as a swarm. Each swarm is composed of individual solutions called particles, initialized with random positions in the solution space with random velocities (update rate). At each iteration, the positions and velocities are updated based on the swarm and particle behavior. Each particle position and velocity is updated using 7 and 8 respectively, and this facilitates the optimization process.

$$x_i^{t+1}=x_i^t+u_i^{t+1} \tag{7}$$

$$u_i^{t+1}=k\left[u_i^t+r_1c_1\left(p_i-x_i^t\right)+r_2c_2\left(p_g-x_i^t\right)\right] \tag{8}$$

t represents the iteration count, x_i is the particle position, u_i is the velocity, $(p_i - x_i^t)$ compares the particle position with its best performance (particle best), $(p_g - x_i^t)$ compares the particle position with the swarm's best performance (global best), c_1 and c_2 are coefficients that represent the trade-off between the influence of the particle best and the global best, r_1 and r_2 are random numbers between 0 and 1, k is the constriction factor. The values of c_1, c_2 and k are set to $c_1 = c_2 = 2.05$ and $k = 0.7298$ to ensure convergence and efficiency in the optimization process [11]. The process was repeated until the difference between the values of global best functions in 50 consecutive iterations are between a tolerance value of 1×10^{-6}. The process is shown in Fig. 3.



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Algorithm 1:
input: Objective function $C_{tobj}$, swarm size $M$,
       CF-PSO parameters
for each particle $i = 1, ..., M$ do
    Initialize particle's position $\mathbf{x}_i$;
    Initialize particle's velocity $\mathbf{v}_i$;
end
Solve DLF to calculate $C_{tobj}$;
Initialize particle's best known position $\mathbf{P}_i$;
Initialize swarm's best known position $\mathbf{P}_g$;
while stopping criterion is false do
    for each particle $i = 1, ..., M$ do
        Update particle's velocity $\mathbf{v}_i$;
        Update particle's position $\mathbf{x}_i$;
        Solve DLF to calculate $C_{tobj}$;
        if $C_{tobj}(\boldsymbol{x}_i) < C_{tobj}(\boldsymbol{P}_i)$ then
            Update particle's best known position $\mathbf{P}_i$ ;
            if $C_{tobj}(\boldsymbol{P}_i) < C_{tobj}(\boldsymbol{P}_g)$ then
                Update swarm's best known position $\mathbf{P}_g$;
            end
        end
    end
end
```

Fig. 3. CF-PSO algorithm

The CF-PSO algorithm was implemented using MATLAB and interfaced with OpenDSS using the provided Component Object Model (COM) server Dynamic Link Library (DLL) as illustrated in Fig. 4.

2.4 Baseline Simulation

An initial load flow was conducted without PV systems to ensure that the base test system did not contain any voltage violations.

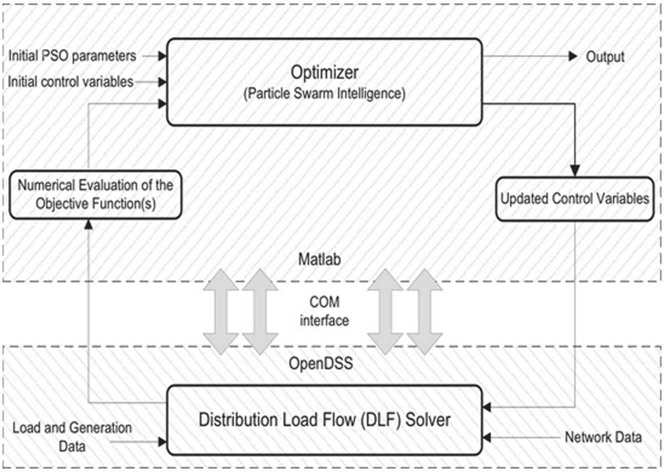

Fig. 4. Platform for CF-PSO MATLAB and OpenDSS loadflow

The PV systems were then connected for the baseline scenario. The PV penetration level is defined as the maximum generation of an individual PV system based on the percentage of total peak load of the system. All 34 nodes have a PV system connected, and the penetration level for the whole system was set at 140% of the total peak load or 60 kW per PV generator. This served as the basis of the power computations for the sizing of the AVR installation and amount of curtailment. AVR installation consists of one AVR based on the result of the method used in optimal AVR positioning. The curtailment scheme implemented is pro rata (equal cost function coefficient π_{gi}).

2.5 Economic Analysis

AVR Installation. Several types of costs were considered when calculating for the equivalent annual cost (EAC) for the AVR over its useful life:

- First cost (investment plus installation cost)
- Annual operation and maintenance costs
- Annual system loss

The EAC for the AVR installation alternative was computed using

$$EAC = FC(A/P, i\%, N) + O + S \tag{9}$$

$$(A/P, i\%, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{10}$$

where FC is the first cost, O is the annual operation and maintenance cost, S is the annual system loss. The system loss is computed from DSO system loss rates and network losses from OpenDSS load flow simulations.

Curtailment Compensation. Calculation for the curtailment compensation considers the PV generation payment scheme used by the DSO to pay the owner of the PV system and results of the OPF. The power curtailed from the generators using the OPF was multiplied to the monthly 2018 Philippine electricity blended generation rates according to different PV generation payment schemes. The payment schemes were: 100%, 50% and 25% of market price, and 3% and 10% maximum curtailment. Maximum curtailment means that the generator owner will receive full market price compensation for any curtailment that goes above a certain percentage. The compensation to be paid over 1 year was the EAC for the curtailment alternative.

Both were compared using ranking comparison. Since this is a service project with no revenue or positive cash flow involved in any calculations, the ranking comparisons only involved determining which alternative yielded a smaller equivalent annual cost.

3 Results

3.1 Initial Load Flow

The initial load flow was carried out for 24 1-h intervals for an average day in each month for 2018.

Shown in red in Fig. 5 are the results of the initial load flow at the month with the highest overvoltage (May at hour 13), without an AVR installed in the system or curtailment applied. On average, the month of May has the highest difference in PV generation and demand at hour 13 or 1:00 PM, so all the AVR sizing and placement is based on the load flow results of this month and hour.

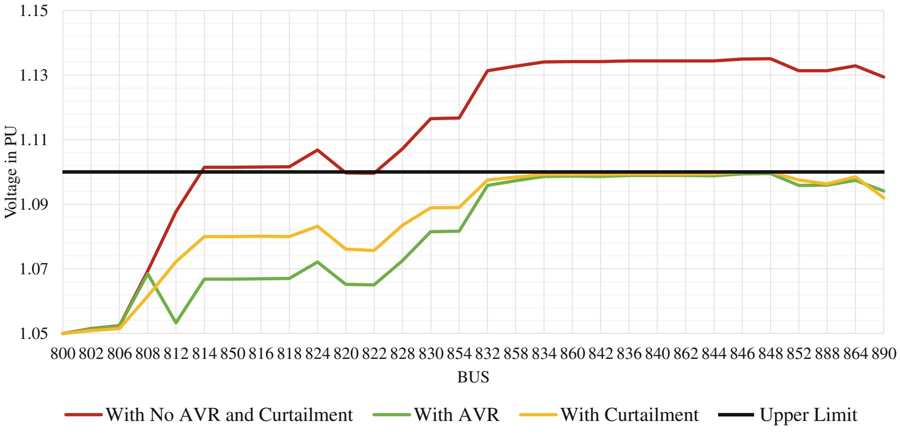

Fig. 5. Voltage profile of buses (phase A) at May Hour 13 (Color figure online)

3.2 Baseline Simulation

Installed AVR. The results of the initial load flow show that the first occurrence of overvoltage in the system is at bus 814. To find the optimal position of the AVR, the first placement of the AVR is between buses 812 and 814. Following the procedure and moving upstream to the substation bus, the optimal location of the AVR is found to be between buses 808 and 812 because it has the lowest voltage drop percentual factor, $F_{at_v}\%$ at 76.24% and it does not have overvoltage throughout the system.

Curtailment of PV Generation. Pro rata or equal curtailment among all PV generators was applied to the system using the objective function $min\,(60 - P_{gi})$ in the CF-PSO algorithm. This type of curtailment yields a generation profile that is the same shape but scaled down from the original. The effect of curtailment on the voltage profile is shown at the hour and month with the worst overvoltage levels in Fig. 5. In total, the amount curtailed for the test system over the year for the baseline simulation was 403 MW.

Table 1. Cost comparison between AVR installation and curtailment compensation for baseline simulation

Compensation scheme	Compensation	AVR installation cost
Full price	\$39,810	\$26,710
0.5 price	\$19,905	
0.25 price	\$9,953	
3% max curtailment	\$32,000	
10% max curtailment	\$17,835	

3.3 Economic Analysis

As presented in Table 1, at the base case or 140% PV penetration, AVR installation is more economical compared to pro rata curtailment at full market price and 3% maximum curtailment compensation. Pro rata curtailment with compensation at 50% and 25% market price, and 10% maximum curtailment are significantly more cost-effective compared to AVR installation.

3.4 Case Studies

Case Study I - Increasing PV Penetration Level. The percentage of the PV penetration is increased by increments of 5% of total peak load starting with the baseline 140% of total peak load.

As shown in Fig. 6, AVR installation is more economical than curtailment compensation at full price and 3% maximum curtailment for all penetration levels. At 50% of full price and 10% maximum curtailment, curtailment is more economical but only up to between 145% and 150%. Curtailment is more economical for penetration levels up to 170% at 25% of full price.

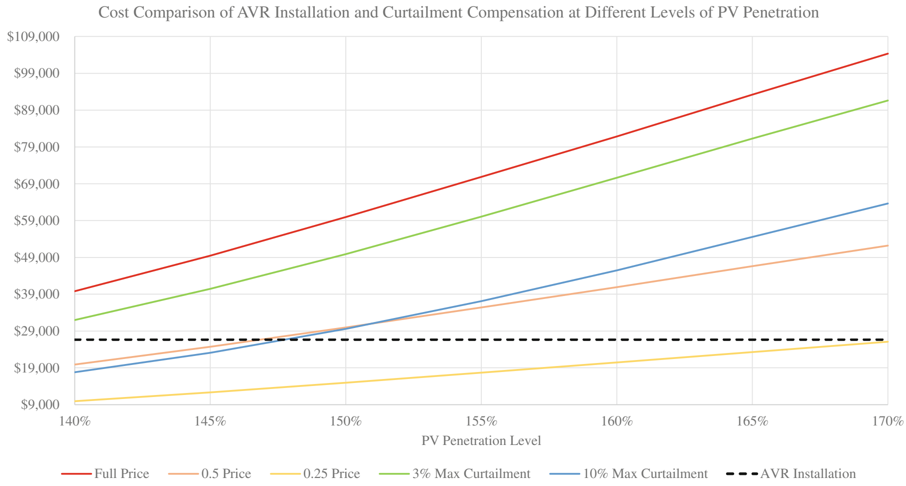

Fig. 6. Cost comparison of AVR installation and curtailment compensation at different levels of PV penetration

Case Study II - Different PV Positioning. Three different placement patterns are tested on the network to see how it affects the overvoltage levels. The PVs are placed at every other node, near the substation, and far from the substation, and compared to the baseline scenario of PVs place at every node.

As presented in Table 2, in the cases where the PVs are positioned at every node (baseline) and at every other node, the cost of AVR installation was cheaper than compensating curtailment at full price and 3% max curtailment, and less economical for the other compensation methods. In the case that the PVs are placed far from the substation, it was more economical to install two AVRs than compensating curtailment for any compensation scheme other than 25% of market price. That being the case, it is more economical to curtail if the majority of PVs in the network are situated near the substation.

Table 2. Cost comparison of AVR installation and curtailment compensation at different positions of PVs in the system

Compensation scheme	Every node	Every other node	Near S/S	Far from S/S
Full price	$39,810	$43,610	$0	$159,094
0.5 price	$19,905	$21,805	$0	$79,547
0.25 price	$9,953	$10,903	$0	$39,773
3% max curtailment	$32,000	$35,398	$0	$146,414
10% max curtailment	$17,835	$19,944	$0	$117,679

Case Study III - Variation of Load Type. Several different percentages of commercial load is mixed in with the baseline scenario of purely residential load: 5% commercial and 95% residential load, 10% commercial and 90% residential load, and 25% commercial and 95% residential load.

At 100% residential and the combination of 5% commercial and 95% residential load, it is less expensive to install an AVR compared to only the full price curtailment compensation scheme as shown in Fig. 7. While at the combination of 10% commercial and 90% residential load, and at the combination of 25% commercial and 75% residential load, all the curtailment compensation schemes are more cost-efficient compared to AVR installation. Generally, as the amount of commercial load mixed in with residential load increases, the more economical it is to curtail PV generation.

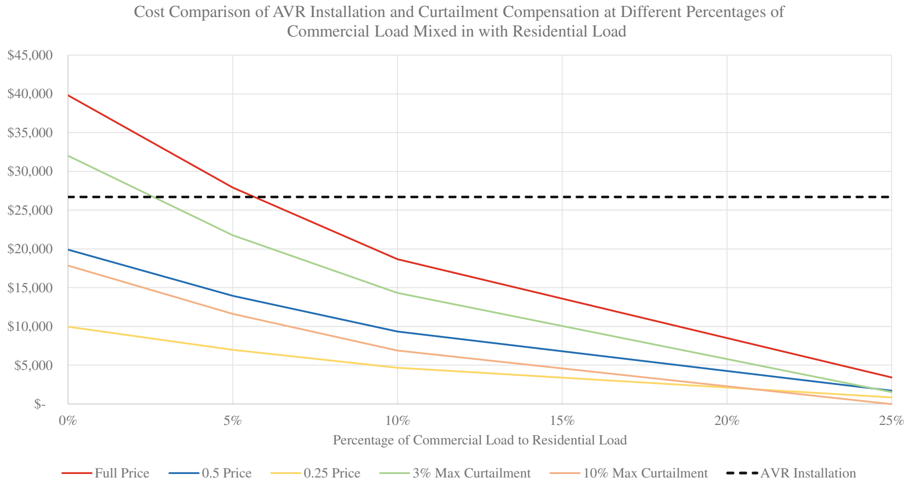

Fig. 7. Cost comparison of AVR installation and curtailment compensation at different percentages of commercial load mixed in with residential load

Case Study IV - Impact of Installing a Large Commercial PV System. This case study aims to find the effect of a sudden large power injection due to installing a large PV generator at one node in a system with only small residential PV systems. Initially, every bus has a 10 kW PV generator, and a single 1.7 MW PV generator is added at one bus.

When the large commercial PV was connected to the buses near the substation it barely caused overvoltage in the system. Conversely, when the large commercial PV was connected to the buses far from the substation, large overvoltages occured at several buses. If we only look at the buses where placement of a large commercial PV causes overvoltage, curtailment compensation (at all schemes) is more economical than AVR installation only when placed at buses 814 and 816. It can be observed that if larger PV capacities are installed nearer to the substation, curtailment is generally more economical than AVR installation, shown in Fig. 8.

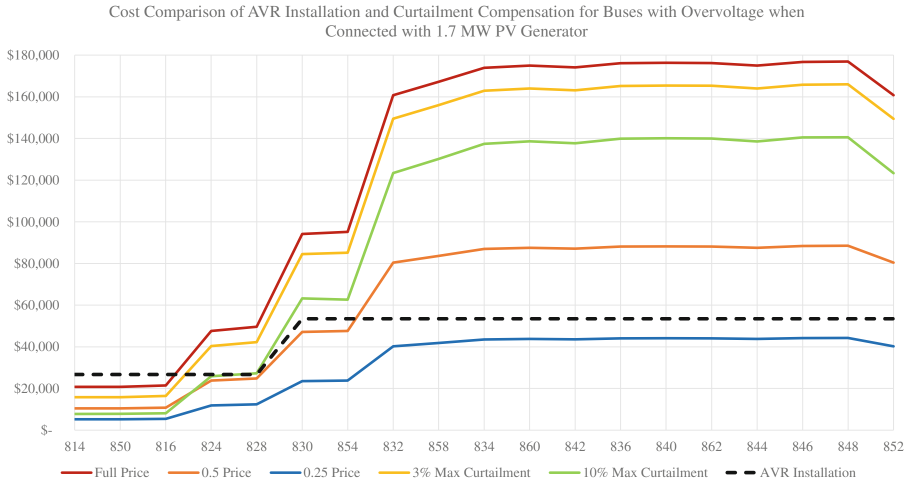

Fig. 8. Cost comparison of AVR installation and curtailment compensation for select buses with large commercial PV

Case Study V - Different Curtailment Arrangement. In technical best, the dispatch optimization is run without the restriction of equal curtailment between each generator, using the objective function $min(\sum_{i=1}^{N}(60 - P_i)$ where P_i is the generation at bus i, and N is the number of buses with generators. In scheduled rotation, a fraction of the generators are fully curtailed (0 kW) at a given day and month and the rest of the generators are dispatched at maximum generation. A different set of generators will be curtailed for each day, following a rotation assigned for each month.

As seen from Table 3, assigning a scheduled rotation yields the highest annual cost out of the three arrangements due to the requirement that any curtailed generator has to be at 0 kW dispatch. This makes curtailed generators near the substation be inefficiently curtailed as they are generally insensitive to power injections, as demonstrated in Case Study IV. It is recommended in this case to compensate the curtailed generators at 50% or 20% of full market price or 10% maximum compensation. Curtailing according to technical best is a more economical curtailment method with dispatch at full price marginally smaller than the baseline AVR annual cost.

Table 3. Cost comparison of AVR installation and curtailment compensation for different curtailment arrangements

Compensation scheme	Pro rata	Tech best	Sched rota
Full price	\$39,810	\$26,477	\$66,484
0.5 price	\$19,905	\$13,239	\$33,242
0.25 price	\$9,953	\$6,619	\$16,621
3% max curtailment	\$32,000	\$25,056	\$64,490
10% max curtailment	\$17,835	\$22,029	\$59,836

Case Study VI - Additional AVR Installation Due to Generation and Load Growth. It may be essential to add AVRs to stabilize the voltage in the system when it increases due to annual generation growth.

As the generation and load is annually increased, there is a need to add AVRs in the network every 3 years so that it can withstand the resulting increase in voltage, as shown in Table 4.

Table 4. Cost analysis of additional AVR installation due to generation and load growth

Case	AVR position	Tap changes	Total annual cost
3 years	808-812; 828-830	20; 31	\$53,438
6 years	808-812; 812-814 828-830; 854-852	26; 28; 54; 89	\$107,371
9 years	806-808; 808-812; 812-814; 828-830; 854-852; 852-832	11; 27; 50; 92; 223; 11	\$167,261

Case Study VII - Combining Curtailment with AVR Installation/s Versus Additional AVR Installations. Curtailment is applied in conjunction with AVR installations as an alternative to purely curtailing generation or additional AVR installations. Since Case Study VI already tackled additional AVR installations, the results of that case study was the basis for the methodology of this case study.

Table 5 shows the economically best combination of each scenario along with the results of Case Study VI. At 3 years of generation and load growth, curtailment in combination with one AVR is more economical than installing an additional AVR for all compensation methods, but only marginally cheaper at full market price compensation. At 6 years of generation and load growth, curtailment in combination with two AVRs is more economical than installing two additional AVRs for all compensation methods. At 9 years of generation and load growth, curtailment in combination with 5 AVRs (one additional AVR) is more economical than installing an additional AVR for all compensation methods.

Table 5. Cost comparison of additional AVR installations and the combination of curtailment with AVR installation

Case	No. of AVRs (Total cost)	Curtailment + AVRs	Compensation scheme	Compensation
3 years	2 AVRs 808-812; 828-830 ($53,438)	Curtailment + 1 AVR 808-812	Full price	$51,003
			0.5 price	$38,857
			0.25 price	$32,783
			3% max curtailment	$44,316
			10% max curtailment	$33,857
6 years	4 AVRs 808-812; 812-814; 828-830; 854-852 ($107,371)	Curtailment + 2 AVRs 808-812; 828-830	Full price	$70,693
			0.5 price	$62,066
			0.25 price	$57,752
			3% max curtailment	$64,252
			10% max curtailment	$54,959
9 years	6 AVRs 806-808; 808-812; 812-814; 828-830; 854-852; 852-832 ($167,261)	Curtailment + 5 AVRs 808-812; 812-814; 828-830; 854-852; 852-832	Full price	$136,719
			0.5 price	$135,935
			0.25 price	$135,542
			3% max curtailment	$135,150
			10% max curtailment	$135,150

4 Conclusion

This research provides a procedure to evaluate between the cost of installing AVRs and the cost of curtailment compensation in a distribution network that is heavily integrated with grid-injecting PV systems. The method makes use of power flow to find the AVR placement and optimal curtailment for a given baseline network, and computing the associated costs for each alternative. The resulting cost computations are projected across the lifetime of the AVR and compared. Upon applying and testing the baseline simulation and several case studies, the researchers found that the procedure can be easily implemented for existing and possible future grid scenarios. It is flexible, as the program used in the IEEE-34 bus system can be easily applied to different radial configurations and use different optimization methods due to the use of OpenDSS and MATLAB. The procedure can be a helpful tool in network planning for DSOs, for example, in the placement of future renewable generation in the network and/or appraisal of non-firm connections. It can also be a useful aid for regulatory bodies and legislators in determining pricing regulations for curtailment compensation. Future work may extend to feasibility studies involving investment in power electronics solutions capable of simultaneously maximizing PV generation and minimizing power quality issues.

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