This article has been accepted for publication in IEEE Transactions on Industry Applications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TIA.2022.3180280

Network-Agnostic Adaptive PQ Adjustment Control for Grid Voltage Regulation in PV Systems

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***Abstract*—The service of grid voltage regulation is required nowadays from Inverter-Based Resources (IBRs) particularly at the lower voltage level. In the transmission network, this is easily managed by leveraging solely the reactive power (Q) capability of the IBR, but in distribution networks which are mix of L and r the voltage magnitude is coupled with both active (P) and reactive power injection. There are methods in the literature designed for these cases that utilize both P and Q in voltage regulation, but they usually require network and load data, which may not be readily available. Furthermore, they often disregard an apparent non-monotonic relation between the inverter terminal voltage and the P/Q ratio risking instability. To fill this gap, this paper introduces a network-agnostic P-Q adjustment technique for photovoltaic (PV) systems or other IBRs. The proposed technique tracks in a step-like manner the reference voltage set point if it is feasible, or the maximum grid voltage otherwise. This allows identification of the critical P/Q ratio without any prior information, at the cost of limited voltage ripple due to a variable step-size strategy implemented. The superior performance of the proposed scheme is validated through simulations in MATLAB-Simulink in a reduced UKGDS 95-bus system and through lab experiments on a scaled down laboratory grade prototype.**

***Index Terms*—PV Inverter, voltage regulation, active power curtailment (APC), reactive power, network agnostic, resistive network**

NOMENCLATURE

δ	Phase angle of substation voltage
θ	Phase angle of line
τ_1	Time constant of low pass filter 1
τ_2	Time constant of low pass filter 2
ϵ_1	Tolerance for steady-state and transient operating condition
ϵ_2	Tolerance for steady-state voltage ripple
APC	Active power curtailment
i^d_{ref}	d-axis reference current of inverter
i^q_{ref}	q-axis reference current of inverter
LPF_1	Low pass filter 1
LPF_2	Low pass filter 2
P	PV active power
P_l	Load active power demand
P_{ref}	Reference active power
P_{sch}	Scheduled active power
P_{st}	Short term voltage flicker
q	Step adjustment resolution
Q	PV reactive power
Q_l	Load reactive power demand
Q_{sch}	Scheduled reactive power
Q_{ref}	Reference reactive power
ΔQ	Step change in reactive power
ΔQ_{max}	Upper bound of reactive power step size
ΔQ_{min}	Low bound of reactive power step size
r	Line resistance
S_{nom}	Nominal kVA rating of the inverter
T_s	Execution time of the algorithm
V_{inv}	Inverter node voltage
V_{fil}	Filtered value of inverter node voltage
V_{inv}	Substation voltage
V_{max}	Maximum achievable voltage
V_{ref}	Reference voltage set point of inverter node voltage
W_1	Window length of reactive power samples
W_2	Window length of voltage samples
x	Line reactance
Z	Line impedance

I. INTRODUCTION

RAPID deployment of photovoltaic (PV) generation poses several challenges to the grid operators, with voltage regulation being among the major ones in distribution networks [?]. Modern day grid codes and standards require that the network voltage is kept within a tight range, usually ±5% of the nominal value [?], [?]. Conventionally, mechanical tap-based on-load tap changing transformers (OLTC), or switch capacitor banks are deployed to fulfill this objective. However, these voltage regulators are not designed to operate very frequently and struggle to cope with the minute-level voltage fluctuation introduced by embedded intermittent supply (e.g. PV systems) and demand (e.g. electric vehicles - EVs) [?]. For this reason, Inverter-Based Resources (IBRs), such as wind, solar and EVs, are increasingly expected to provide support during overvoltage and undervoltage conditions. The topic of overvoltage support from PV systems has been thoroughly explored in the literature [?], [?], [?], [?] and is technically straightforward. However, voltage regulation at undervoltage conditions is more challenging and is the focus of this paper.

The most common and straightforward approach for voltage regulation is adjustment of reactive power (Q) based on a static $Q-V$ droop characteristic [?], [?]. Although the droop logic

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Paper No. 179 was presented in 2020 21st National Power System Conference (NPSC), IIT Gandhinagar, India, December 17-19, 2020 and is under consideration for publication in the IEEE Transaction on Industry Application by the IEEE-IAS Power Systems Engineering Committee.

manages effectively power sharing among nearby resources, its inherent open loop nature leads to residual voltage regulation mismatches. To address this, dynamic droop-based alternatives are discussed in the literature [**?**], [**?**], [**?**]. In [**?**], an adaptive droop law is proposed with the objective of ensuring system stability and zero steady-state error. In [**?**], an additional active power (P) dependent term is used on top of the static $Q-V$ droop characteristics to minimize the effect of active power variation of the PV inverter. In [**?**], voltage sensitivity information is used to determine the Q reference from a proposed P-Q droop law.

All the aforementioned techniques aim at regulating the grid voltage by managing solely the Q injection capability of IBRs. However, at sub-transmission or distribution levels where PV farms or these IBRs are most commonly installed, the network is predominantly resistive or combination of L and r where, r/x ratio more than 1. In these cases, the voltage magnitude is strongly coupled with both Q and P power flows, and Q alone may be insufficient in voltage regulation [**?**], which in turn often leads to oversizing of the inverters [**?**]. A more effective approach would be simultaneous adjustment of both P and Q components in these networks. Of course modification of the active power is not a trivial task and presupposes that any mismatch is readily balanced from the substation. In addition, downward P adjustment is straightforward in PV plants, but upward increment requires a source of power reserves, either in the form of energy storage [**?**], [**?**], [**?**] or by keeping a power headroom (curtailing power) in the PV inverter. The former option is the most obvious but comes with additional installation and maintenance costs [**?**]. The latter approach, referred to often as active power curtailment (APC), under-utilizes the installed PV capacity but is a simple way to make existing PV plants more grid-friendly [**?**].

Regardless of the power reserves approach, there are quite a few voltage regulation methods in the literature that leverage both the P and Q capacity in PV systems. In [**?**], a $P-Q-V$ droop control technique is proposed, according to which the active power is adjusted to mitigate the voltage drop due to load active and reactive power demand. In [**?**] an APC technique for wind farm is proposed. In that work, APC is done to match the reactive power capability of the wind generator with the reactive power demand of the system so that the reference set point for the voltage is achieved. In [**?**], coordination between different voltage regulation techniques like voltage-dependent power factor, APC, $Q-V$ droop control are discussed. In that study, APC is enabled only when the system voltage exceeds a pre-defined voltage level. In that case, Q reference and consequently P is curtailed depending on the system voltage level. In [**?**], the static $Q-V$ droop characteristic is merged with an APC technique to enhance the voltage regulation performance of the PV inverter. In that paper, a short-term PV generation forecasting technique is used to determine the amount of active power curtailment. Optimization-based APC techniques are also discussed in [**?**], [**?**]. In [**?**], a zone based volt-var optimization technique is proposed to minimize the tap operations of the voltage regulators installed upstream of the network. In [**?**], a distributed optimization technique is proposed to maintain the grid voltage while minimizing the line loss. Both these techniques aim at minimizing the amount of active power curtailment.

Fig. 1: Single node equivalent circuit of the network as seen from the PV inverter terminal

All these methods exploit the additional flexibility given by P adjustment, but they assume a monotonic relation between P and V much like between Q and V. However, our previous study [**?**] shows that in the case of undervoltage, increasing Q at the expense of P beyond a certain point may lead to grid voltage drop rather than boost. In other words, there is a *non-monotonic* relation between the P/Q ratio of the inverter and the node voltage. This phenomenon is disregarded in the aforementioned techniques and as a result they may deliver poor regulation performance or controller instability at certain conditions. Moreover, most of these methods heavily rely on lines and load data, information which varies in time and is not readily available to the PV plant controller. This dependence poses a barrier towards application in actual systems.

In light of these limitations, this paper proposes a network-agnostic PQ adjustment technique for voltage regulation by PV systems, as an extension of our previous study [**?**]. This algorithm adjusts the P and Q components in subsequent steps in search for the reference voltage set point V_{ref}, but it converges to the maximum voltage V_{max} instead when the former is not reachable. Inspired by the way maximum power point tracking (MPPT) algorithms work, this method overcomes the non-monotonicity problem and locates the V_{max} voltage peak without any prior knowledge about the network, i.e. it is *network-agnostic*, in stark contrast to the existing literature. Compared to [**?**], the new "Adaptive PQ+" algorithm features the following improvements:

- It adopts a variable step mechanism to contain the voltage ripple induced by the step adjustments, which was previously found excessive in some cases Voltage ripple is correlated with the short term voltage flicker (P_{st}), and consequently the P_{st} values with all the voltage regulation techniques under consideration are compared.
- The methodology for the selection of the parameters of the proposed algorithm is now fully detailed
- More comprehensive validation is performed, with more realistic simulations.
- Experimental validation is performed on a scaled-down prototype for two case studies.

The remaining of the paper is organised as follows: The relation between grid voltage and P/Q ratio is discussed in Section II. In Section III, the proposed Adaptive PQ+ algorithm is described, detailing the core function, the variable step mechanism and the parameters selection methodology. The proposed technique is verified through simulation and experimental results in Section IV, followed by the conclusions in Section V.

II. RELATION BETWEEN VOLTAGE AND P/Q RATIO

Fig. 1 represents the equivalent circuit of the network as seen from the PV node. When V_{inv} is high and needs to

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be reduced (overvoltage condition), the PV plant can increase the Q consumption up to the VA inverter rating, and then it can curtail some P to further lower the terminal voltage and simultaneously free some space up for additional Q increment; the two adjustments here have a consistent effect on voltage, and therefore linear control is appropriate.

This is not true at undervoltage conditions. To increase V_{inv}, the PV inverter can easily up-regulate its Q injection up to the inverter rating; however, further Q adjustment at the expense of curtailing some P has the conflicting effect of raising the voltage due to the former, but lowering due to the latter. The relation between the voltage and mathematical relation between the P and Q of the inverter is derived and it is shown that there is only one maxima in the non-monotonic relation between V and P, and Q of the inverter.

A. Mathematical Analysis

Using circuit analysis of Fig. 1, the active and the reactive power flow in the equation are found as,

$$\frac{(P_l - P)}{3} + \frac{V_{inv}^2}{Z}\cos\theta = \frac{V_{inv}V_{sub}}{Z}\cos(\delta-\theta) \tag{1}$$

$$\frac{(Q_l - Q)}{3} + \frac{V_{inv}^2}{Z}\sin\theta = \frac{V_{inv}V_{sub}}{Z}\sin(\delta-\theta) \tag{2}$$

where, P_l and Q_l are the load active and reactive power demand, and P_{pv} and Q_{pv} are the active and the reactive power supplied by the PV inverter. Variables δ and θ are the substation voltage and phase angles of line impedance respectively, considering the PV node voltage to be the reference (i.e. 0 angle). V_{sub}, and V_{inv} are the substation and inverter node voltage magnitude. Z is the magnitude of the line impedance. Assuming, the load power (P_l and Q_l) to be zero, as load power demand does not affect the result of the analysis, squaring and adding (1) and (2) yields

$$V_{inv}^4 - \left[2\frac{P}{3}r + 2\frac{Q}{3}x + V_{sub}^2\right]V_{inv}^2 + \frac{(P)^2+(Q)^2}{9}Z^2 = 0 \tag{3}$$

Equation (3) relates the resulting V_{inv} voltage for a particular P_{pv}, and Q_{pv} injection. In (3) r and x are the resistance and reactance of the line respectively, given as $Z\cos\theta$ and $Z\sin\theta$ respectively. In order to have the maximum voltage support from the PV inverter during a heavy undervoltage event, it is required to operate the PV inverter at its nominal rating, i.e. to leverage all the available P and Q capacity

$$P^2 + Q^2 = S_{nom}^2 \Rightarrow P = \sqrt{S_{nom}^2 - Q^2}$$

Replacing the expression for P in (3) results in:

$$V_{inv}^4 - \left[2\frac{\sqrt{S_{nom}^2 - Q^2}}{3}r + 2\frac{Q}{3}x + V_{sub}^2\right]V_{inv}^2 + \frac{S_{nom}^2}{9}Z^2 = 0 \tag{4}$$

Fig. 2: PV node voltage dependence on the r/x ratio of the Thevenin equivalent network [**?**]

Differentiating (4) w.r.t Q yields

$$\frac{dV_{inv}}{dQ} = \frac{\left[\frac{2r}{3}\frac{Q}{P} - \frac{2}{3}x\right]V_{inv}^2}{4V_{inv}^3 - \left[2\frac{P}{3}r + 2\frac{Q}{3}x + V_{sub}^2\right]V_{inv}} \tag{5}$$

For maximum value (peak) of V_{inv}, $\frac{dV_{inv}}{dP} = 0$. From (5), there is *only one solution* which is,

$$\frac{P}{Q} = \frac{r}{x} \tag{6}$$

Therefore, this shows under a particular operating condition there would a single maximum point in the non-monotonic relation between V and P and Q.

Fig. 2 illustrates an example of the $V_{inv} - P/Q$ relation for different values of r/x ratio, which clearly shows that it is non-monotonic and that the voltage peak appears when (6) holds true. Up-regulating Q by curtailing P, i.e. decreasing the P/Q ratio (moving from right to left), boosts the voltage up to the critical r/x value; further adjustment shifts the operating point past the voltage peak and yields the opposite effect. Therefore, a conventional linear controller that disregards this non-monotonic relation risks voltage instability if it overtakes the voltage peak at any time.

Furthermore, it is worth noting that the r and x values of the Thevenin equivalent network represent the combination of lines, loads and other network equipment as reflected for a particular power flow. Therefore, the *r*/*x* ratio is not a constant value but varies with the operating conditions and network configuration, and hence cannot be known a priori. Real-time estimation of this ratio is a challenging task.

III. PROPOSED ADAPTIVE PQ+ ALGORITHM

The previous discussion reveals that a conventional linear control approach is not robust; it requires a regulation limit on the P/Q ratio up to the critical r/x value, which is changeable and unknown, thus risking instability. To cope with this challenge, the proposed Adaptive PQ+ algorithm adopts an alternative hill-climbing approach that traverses the non-monotonic characteristic unhindered. The full picture of the proposed control is shown in Fig. 3. The inverter terminal voltage V_{inv} is low-pass filtered (LPF_1) to reject measurement noise and is fed into the "PQ Adjustment" block. This determines the amount of scheduled reactive power Q_{sch} for the PV inverter, which is fed to a second low pass filter (LPF_2) to yield smoother Q_{ref} commands. The latter then informs the standard power and current inverter inner loops to generate the modulation signals. The "Variable Step Size Calculation" block is responsible for adjusting the step size ΔQ to contain the V_{inv} ripple within a defined tolerance band.

Fig. 3: Block diagram of the proposed control scheme

Fig. 4: Flowchart of adaptive PQ adjustment algorithm

A. Adaptive PQ Algorithm

The flowchart of the proposed algorithm is shown in Fig. 4. The main objective is to decide the level of reactive power (Q_{sch}) that leads to the V_{ref} target primarily, or V_{max} as a last resort. This method adjusts Q_{sch} in sequential ΔQ steps looking for the voltage peak, except if V_{ref} is reached first. Please note that ΔQ is not a fixed quantity, but it is continuously adjusted as discussed later.

The working principle of the Adaptive PQ+ algorithm is explained with the two indicative plots of Fig. 5. Fig. 5 (a) corresponds to the common case that V_{ref} is achievable (lower than V_{max}), where the operating point moves from right to left till it reaches the target and oscillates around it. In contrast, V_{ref} is infeasible in Fig. 5 (b) (higher than V_{max}), and therefore the operating point reaches V_{max} and converges there, rather than overtaking it and moving to the right-hand side. This way, optimal voltage regulation performance is delivered and the critical P/Q ratio is also identified.

B. Variable Step Size Implementation

Fig. 5 clearly shows that the slope of $V_{fil} - Q_{sch}$ relation strongly depends on the operating point, and therefore a fixed step size ΔQ would lead to very different voltage ripple levels. This is the main weakness of [**?**], since an uncontrollable ripple may be too much for power quality reasons or too little to detect the voltage changes with the Adaptive PQ algorithm. The proposed adaptive step size method here manages the situation by distinguishing between the two different operating conditions: "steady-state" and "transient". The former case refers to when the operating point has reached its target (V_{ref} or V_{max}) and oscillates around it, so the ripple needs to be regulated around an ϵ_2 limit. The transient condition corresponds to when the operating point traverses the characteristic in search for its target, in which case ΔQ should be large to make the transition fast.

The full picture is given in the flowchart of Fig. 6. The algorithm employs two running windows W_1 and W_2 (i.e. sampling buffers) which are used in the identification of the operating mode and voltage ripple calculation respectively. W_1 stores the most recent Q_{sch} values (number of samples $len(W_1)$) to figure out whether in steady-state or transient mode. This mechanism is explained also with the plots of Fig. 7 (a) and (b). When in transient mode, Q_{sch} is constantly increasing (or decreasing) and every value is higher (or lower) than the previous, thus the sign of each step will be always positive (or negative) (see Fig. 7 (a)). On the contrary, in steady-state the step sign oscillates between positive and negative values, as Fig. 7 (b) shows. Therefore, the average of the step signs within the window should be close to +1 (or -1) in transient and close to 0 in steady-state. This is the premise of the central branch in Fig. 6, in which the *absolute* step sings average is compared to a tolerance $\epsilon_1 = 0.5$ to infer the operating mode.

Fig. 5: Indicative figure of feasible and infeasible reference voltage: (a) V_{ref} is feasible ($V_{ref} < V_{max}$), (b) V_{ref} is infeasible ($V_{ref} > V_{max}$) [**?**]

Fig. 6: Flowchart of adaptive step size algorithm

Fig. 7: Indicative figures of steady-state and transient operating conditions: (a) V_{fil} and Q_{sch} are in transient, (b) V_{fil} and Q_{sch} are in steady-state

The operating mode decides how the ΔQ step is adjusted. When in transient mode, the step is always increased to reach the voltage target promptly, whereas in steady-state operation the step is regulated up or down to meet the grid voltage ripple requirements. This last task is performed with W_2, which keeps record of the recent V_{fil} samples and captures the ripple; this is then compared to the ripple target ϵ_2 to determine up- or down- regulation of the ΔQ step. These steps adjustments are made with a resolution of q and abide by a lower ΔQ_{min} and upper ΔQ_{max} bound. The selection of all these parameters are discussed later in this section.

C. Inner Control Layers

The inner loops include a power control layer and the conventional current control layer, as shown in Fig. 8. The objective of the former is to saturate the power commands within their limits, i.e. Q_{ref} within the inverter rating $\pm S_{nom}$ and P_{sch} inside the remaining headroom $P_{max} = \sqrt{S_{nom}^2 - Q_{ref}^2}$ (reactive power priority). The scheduled active power level P_{sch} is an input, normally the maximum available PV power or another deloaded value in case of curtailment. The maximum PV power can be estimated in real-time using mathematical models such as the ones in [**?**], [**?**].

The saturated power commands are algebraically translated to current references, which in turn drive a conventional current PI controller regime formulated in dq0 frame. The PWM module that generates the switching pulses is also included.

D. Control Parameter Selection

The parameters of the inner loops of the inverter control are well explored in the literature, thus here the discussion is limited to the parameters of the proposed Adaptive PQ+ algorithm, that is the flowcharts Fig. 4 and 6.

1) LPF_1 time constant τ_1: This low pass filter is used to reject the voltage measurement noise from V_{inv}, which is a RMS quantity. Therefore, in the steady-state V_{inv}

Fig. 8: Block diagram of inner power and current layers

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value does not change. During a transient a change in the order of few Hz is expected in V_{inv} value based on load driven dynamics. So a cutoff frequency around 25-50 Hz is reasonable.

2) LPF_2 time constant τ_2: This low pass filter is used to smooth out the step change of Q_{sch} according to the operator's requirements. A cut-off frequency in the order of 1-2 Hz is considered here sensible, but it could be lower for even smoother response.
3) Execution period T_s: This refers to the execution frequency of the entire algorithm incorporating both Adaptive PQ and Variable Step Size mechanisms. T_s should be sufficiently large for all dynamics to settle after any step. The network dynamics are very fast and can be ignored, while LPF_2 is much slower than LPF_1 and dominates the settling time. Therefore, T_s is selected as 4 times τ_2, based on the common empirical rule for first-order filters.
4) Window length of W_1: W_1 is used to detect the operating mode, steady-state or transient. For this purpose, it should hold an even number of samples greater or equal to 4; a lengthier window gives a more robust, albeit slower, estimation.
5) Window length of W_2: This window is used for the grid voltage ripple calculation and requires at least 2 V_{fil} samples. It is recommended though to use an even number greater or equal to 4 for more reliable results.
6) Tolerance ϵ_1: This criterion is applied to the running average of step signs within W_1 to infer the operating mode. This average should be 1 in transients and 0 in steady-state, so ϵ_1 is selected midway that range at 0.5.
7) Tolerance ϵ_2: The ripple target is application dependent and is imposed by the operator to strike a balance between power quality and reliable algorithm operation. ϵ_2 should be decided at the planning stage depending on minimum flicker requirement. Hence, ϵ_2 should not be too high due to power quality impact (e.g. as per IEEE 1453-2015 standard [**?**]), not too low because the algorithm would struggle to perceive the voltage changes. In fact the optimal value of ϵ_2 does not depend on the PV control but on external parameters, primarily noise level and network impedance. A value 0.1-0.2% of ϵ_2 is deemed sufficient for reasonable noise conditions.
8) Maximum step ΔQ_{max}: The upper bound of the step size should be high enough to achieve the ϵ_2 ripple at the voltage peak V_{max}, but not too high to impede the step adjustment. Empirically it is found that 10% of S_{nom} is a good value, but higher levels would work as well.
9) Minimum step ΔQ_{min}: The lower bound is not very critical, but needs to be a positive value greater than 0. It is recommended to set this equal to the adjustment resolution q.
10) Step adjustment resolution q: The step size range from ΔQ_{min} to ΔQ_{max} should be split into 5-10 levels, to achieve a resolution that balances fine tuning and adjustment speed.

It is noteworthy that the proposed algorithm is deterministic in nature. Therefore, the proposed algorithm does not require any additional computation requirement, and can be very well in any commercial digital signal processor (DSP).

Fig. 9: System used in simulations based on UKGDS-95 bus network

Fig. 10: Simulation results: loading profile of Load 3

IV. SIMULATION RESULTS

A. Single Inverter Case

The proposed technique is validated through simulations in MATLAB-Simulink for the system shown in Fig. 9. This system is loosely based on UKGDS-95 bus radial distribution network where, lines and loads are aggregated to improve the simulation time. The system parameters are given in Table. I and the line and load parameters in the Fig. 9.

The grid voltage fluctuation is emulated by manipulating the loading profile of Load 3 as shown in Fig. 10. It is worth mentioning that in a real case the load would vary more smoothly, but here it is deliberately assumed to change in an abrupt step manner to clearly evaluate the merits of the techniques under consideration.

In the following discussion, the voltage regulation performance of the proposed Adaptive PQ+ technique is compared with another three approaches: (i) the conventional Q injection (Conv. Q) which exploits only the reactive power capability of the inverter; (ii) the conventional active power curtailment (Conv. PQ), where active power adjustment through APC is considered as well, but disregarding the non-monotonicity relation; and (iii) our previous version of Adaptive PQ algorithm [**?**] that doesn't feature adaptive step and ripple regulation. The parameters of the proposed Adaptive PQ+ are given in Table II.

Fig. 11 shows the voltage and power profiles with all four methods, while Fig. 12 provides further detail on the control signals of the Adaptive PQ+ method. In the first phase t_1, the

TABLE I: Specifications of the Simulated System

Symbol	Parameter	Value
S_{CCM}	Nominal Rating of inverter	1.05 MVA
f_{nom}	Nominal frequency	50 Hz
V_{nom}	Nominal line-line voltage	11 KV (RMS)
f_s	Switching frequency	10 kHz

TABLE II: Parameters of the Adaptive PQ+ algorithm

Parameter	Value
LPF time constants	τ_1=40 ms, τ_2=500 ms
Execution period	T_s=2 s
Window lengths	W_1=4 samples, W_2=4 samples
Tolerance	ϵ_1=0.5, ϵ_2=0.15%
Step size	ΔQ_{min}=20 KVAr, ΔQ_{max}=120 KVAr, q=20 KVAr

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TABLE III: Comparison of Voltage Regulation Performance

Duration	$\mathrm{V}_{\mathrm{ref}}$	$\mathrm{V}_{\mathrm{max}}$	Steady-state value of V_{fil} (pu)				Steady-state voltage ripple (%)	
	pu	pu	a	b	c	d	c	d
t_1	**1.01**	1.017	**1.01**	**1.01**	**1.01**	**1.01**	0.49	0.14
t_2	1.01	**0.977**	0.972	0.922	**0.977**	**0.977**	0.11	0.09
t_3	1.01	**0.995**	0.99	0.94	**0.995**	**0.995**	0.12	0.10
t_4	**0.975**	0.995	**0.975**	0.94	**0.975**	**0.975**	0.26	0.15

a= Conventional Q, b= Conventional PQ, c= Adaptive PQ [**?**], d= Adaptive PQ+

Fig. 11: Simulation results for four study-case methods: (a) Reactive power profile, (b) Active power profile , (c) PV node voltage profile

Fig. 12: Control signals of the Adaptive PQ+ method: (a) Reactive power profile, (b) Operating mode, (c) Grid voltage ripple, and (d) ΔQ step

loading in Load 3 is normal and all methods readily regulate V_{fil} to its reference value V_{ref} (black dotted line in Fig. 11 (c)). This is because the required Q_{pv} for this task is within the reactive power capability of the inverter and there is no need for active power curtailment. This is why P remains equal to the maximum power P_{mpp} for all methods in Fig. 11 (b). The two adaptive algorithms induce some ripple on the grid voltage, which is substantially less in Adaptive PQ+ compared to [**?**] due to the adaptive step mechanism. This is more clearly shown in Fig. 12 (c)-(d), where the voltage ripple is rapidly reduced to meet the ϵ_2 target in the former plot, as a result of the step size modification in the latter plot.

In the next phase t_2, a substantial load increase (see Fig. 10) leads to a voltage sag in Fig. 11 (c). Now, V_{ref} becomes infeasible, as V_{max} falls to 0.977 pu (pink dotted line). In response to this sag, Conv. Q performs suboptimal regulation reaching up to 0.972 pu (blue line), as the reactive power capacity does not suffice. Interestingly, the Conv. PQ method reaches and overtakes V_{max} in search of the infeasible V_{ref} target, and as a result it curtails all available P_{pv} (red lines in Fig. 11 (b)-(c)). This not only yields the lowest voltage (0.922 pu), but also massive amounts of unnecessary active power curtailment. This highlights why it is important to take the non-monotonic relation between P, Q and V into account when adjusting both power components in voltage regulation.

The two adaptive PQ methods ensure operation around the critical P/Q ratio that yields V_{max} (Fig. 11 (c), green and purple lines respectively) by curtailing some P and increasing Q (red and purple lines in Fig. 11 (a), and (b)). This is in contrast to the conventional approaches that do not attain this value. Fig. 12 (b) shows when Adaptive PQ+ detects the transient condition, during which the ΔQ step increases rapidly in Fig. 12 (d) to regulate the ripple below ϵ_2 in Fig. 12 (c). The steady-state voltage values and ripple are given for all methods and phases in Table. III.

A subsequent load decrease in the next phase t_3 elevates V_{max} to 0.995 pu, (Fig. 11 pink dotted line) which still remains lower than the target. Therefore, the four methods behave pretty much like before, with Conv. Q underdelivering due to the limited reactive power margin available, the Conv. PQ technique stuck at a $P_{pv} = 0$,$Q_{pv} = S_{nom}$ situation, and the two adaptive methods getting good hold of the optimal P/Q ratio (see Fig. 11). This phase proves that the two algorithms do not lose track of the voltage peak during load changes. Here the voltage ripple is quite similar in the two adaptive approaches, as it corresponds to voltage peak operation and is close to the ϵ_2 limit.

In the final phase t_4, V_{ref} is reduced down to 0.975 pu without any load change, which renders it now an achievable target (see Fig. 11(c)). The required Q_{pv} is within the reactive power margin of the inverter in this phase, and therefore all methods can achieve the target without any P curtailment. Still, however, Conv. PQ remains trapped in the previous 100%-curtailment condition and requires some kind of manual intervention to restore its operation; this is another indication of the risk in neglecting the non-monotonicity relation. The two adaptive algorithms are mobilized by the reference change and they meet the new target, although admittedly more slowly compared to Conv. Q. It is worth noting that the final voltage ripple in Adaptive PQ+ is visibly lower than that of [**?**] in Fig. 11(c); this is justified by Fig. 12(c)-(d) that indicates how the step is reduced to maintain the required amount of ripple.

The overall voltage regulation performance of the aforementioned techniques is captured in Table. III. From the steady-state V_{fil} values it is clear that [**?**] and the proposed Adaptive PQ+ technique deliver the most favorable performance by meeting always either V_{ref} or V_{max}, whichever is lower. Conv. Q is reliable but does not fully leverage the inverter capacity, underperforming in phases t_2 and t_3. The Conv. PQ management technique is prone to instabilities, as it disregards the aforementioned non-monotonic relation and gets trapped at $P_{pv} = 0$ resulting in poor voltage profile.

In terms of voltage ripple, the two conventional methods are expectedly superior and do not exhibit any measurable ripple in simulations setting due to the smooth linear control action. However, between the adaptive approaches, the proposed Adaptive PQ+ algorithm is far superior to [**?**], yielding ripple always equal to or less than the 0.15% target, which is up to 2-3 times less than [**?**] due to the variable step size mechanism.

In fact, the main conclusion from this investigation is that the Adaptive PQ+ method strikes a balance between power quality and voltage regulation performance: it fully leverages the VA capacity of the inverter at the cost of limited and fully controllable induced voltage ripple.

This article has been accepted for publication in IEEE Transactions on Industry Applications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TIA.2022.3180280

Fig. 13: System used for simulation for multiple inverter cases

Fig. 14: Simulation results: loading profile of Load 7

B. Multiple Inverter Case

This case study explores operation of multiple inverters employing the proposed control scheme in terms of grid stability. To investigate the stability issue with the proposed Adaptive PQ+ technique, the network shown in Fig. 9 is augmented in line with UKGDS 95 bus system as shown in Fig. 13. Two cases are considered for this investigation where an additional PV plant PV2 is connected at bus 7 or bus 4 respectively. The loading profile of load 3 is kept same as in Fig. 10. The loading profile of load 7 is given in Fig. 14. Furthermore, for this investigation V_{ref} is set at 1.01 pu till 120 s, and subsequently it is reduced to 0.97 pu for both the inverters. The reactive power, active power and node voltage of PV1 and PV2 with the Adaptive PQ+ algorithm for the two cases is shown in Fig. 15.

For case-1, i.e. when PV2 is connected at bus 7, each inverter regulates successfully and individually each target, without any undesirable interaction or dynamic behaviour of concern related to voltage stability of the network. For case-2, i.e. when PV2 is connected at bus 4, despite close electrical distance between PV1 and PV2, both the inverters work seamlessly, reaching their target set-point (V_{ref}) or compromising with maximum available voltage (V_{max}). There is no indication of oscillation or interaction regardless of the closer electrical connection between them. Surely, the relatively low frequency of the P/Q adjustments (i.e. every 2 seconds), allows sufficient time for any network related dynamics to settle and avoids the relevant oscillations.

V. EXPERIMENTAL RESULTS

The proposed technique is experimentally validated on a scaled-down grid-connected inverter prototype. The experimental setup is depicted in Fig. 16, while the network configuration corresponds to the simple circuit of Fig. 1. The inverter comprises an FNA22512A IGBT module (ON Semiconductor make) for the switching devices and an TMS320F28335 Delfino microcontroller (Texas Instrument make). A series resistance/inductance branch is used as the AC load and the grid is formed by a regenerative grid simulator (CHROMA Make, 61830 series). Here, the voltage variation is emulated by directly varying the grid simulator output, rather than by changing the loading profile, for simplicity reasons. The parameters of the experimental system are given in Table IV.

Fig. 15: Simulation results for two case studies: (a) Reactive power profile, (b) Active power profile , (c) PV node voltage profile

TABLE IV: Specifications of the Experimental System

Symbol	Parameter	Value
S_{CCM}	Nominal Rating of inverter	650 VA
f_{nom}	Nominal frequency	50 Hz
V_{nom}	Nominal line-line voltage	55 V (RMS)
f_s	Switching frequency	10 kHz
Load	R_L, X_L	R_L=5.1 Ω, X_L=1.15 Ω
Line	r_L, x_L	r_L=2.1 Ω, x_L=1.15 Ω

Fig. 16: Experimental setup

Fig. 17: Experimental results: Inverter voltage variation (V_{fil}) imposed by the grid simulator

A. Load Transient

Like in the simulations, the proposed Adaptive PQ+ technique is compared to the other three alternatives during abrupt step-changes in load. In the experiment, the load change is emulated by changing the voltage of the grid emulator in steps. The experiment lasts for 15 min, which is too long for the data acquisition (plotting) of the oscilloscope due to length limitations. Therefore, the logging capabilities of the microcontroller are employed instead, by capturing the relevant signals at a 2 s interval and later passing the data vectors to MATLAB for plotting. The control parameters remain the same as in simulations (Table II), except for modified ΔQ_{max}=120 VAr, ΔQ_{min}=10 VAr, q=10 VAr, and ϵ_2=0.35% to account for the scaled-down system rating.

In absence of separate sensors on the substation node, the grid voltage fluctuation is captured in the inverter node instead in Fig 17, while having the inverter operating at unity power factor. In other words, Fig 17 shows how the inverter node voltage would be without the voltage regulation control. The instantaneous waveforms of inverter node voltage, and inverter output current for this operating condition is shown in Fig. 18. Inverter's power and voltage profiles are depicted in Fig. 19 for all methods. Table V aggregates the performance metrics. In the first phase t_1, all methods regulate the voltage at the V_{ref} value (black dotted line in Fig. 19 (c)), although with different ripple levels. Table V shows that the two linear-controlled methods and the proposed Adaptive PQ+ technique yield very limited ripple around 0.1-0.3%; in contrast, the basic adaptive

Fig. 18: Experimental results: (a) Inverter node voltage (0.52 pu/div), (b) Instantaneous inverter node voltage (phase a) (20 V/div), (c) Instantaneous inverter output current (phase a) 5 A/div

Fig. 19: Experimental results for the four study-case methods for load transients: (a) Reactive power profile, (b) Active power profile, (c) PV node voltage profile

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TABLE V: Comparison of Voltage Regulation Performance

Duration	V_{ref}	$V_{\max}$	Steady-state value of V_{fil} (pu)				Steady-state voltage ripple (%)				Short term voltage flicker (P_{st})			
	pu	pu	a	b	c	d	a	b	c	d	a	b	c	d
t_1	**1.01**	1.06	**1.01**	**1.01**	**1.01**	**1.01**	0.10	0.08	2.16	0.32	0.3645	0.3604	0.6617	0.4689
t_2	1.01	**0.988**	0.975	0.743	**0.988**	**0.988**	0.14	0.24	1.34	0.21	0.4339	0.4791	0.5025	0.4445
t_3	**1.01**	1.02	0.99	0.791	**1.01**	**1.01**	0.07	0.25	1.45	0.34	0.3745	0.5336	0.4415	0.3768
t_4	1.01	**0.976**	0.962	0.704	**0.976**	**0.976**	0.19	0.38	0.83	0.18	0.3993	0.5346	0.4205	0.4304
t_5	**0.973**	0.976	0.962	0.704	**0.973**	**0.973**	0.11	0.21	0.73	0.32	0.3903	0.5386	0.4173	0.3951

a= Conventional Q, b= Conventional PQ, c= Adaptive PQ [**?**], d= Adaptive PQ+

Fig. 20: Experimental results: (a) P_{pv} profile (b) Inverter voltage (V_{fil}) due to change in P_{pv} without voltage control

Fig. 21: Experimental results: (a) P_{pv} profile (140 W/div), (b) Instantaneous inverter node voltage (phase a) (20 V/div), (c) Instantaneous inverter output current (phase a) 5 A/div

algorithm of [**?**] leads to high ripple more than 2%, which is also visibly excessive in the red line of Fig. 19(c).

The phase t_2 refers to a grid voltage drop that renders V_{ref} infeasible, with the four algorithms responding like in the simulations (Fig. 19). Conv. Q delivers suboptimal voltage as the reactive power capacity alone does not suffice (blue line); Conv. PQ reaches V_{max} momentarily, but quickly overtakes the peak and locks onto a full-curtailment situation (orange line); the two adaptive algorithms track V_{max} successfully, but the steady-state ripple is almost six times higher with [**?**] compared to proposed Adaptive PQ+ technique, as specified in Table V.

A limited increase in the substation voltage in t_3 renders V_{ref} marginally attainable, but only when the P flexibility is explored. This is why Conv. Q still underperforms, and only the two adaptive approaches meet the target in Fig. 19(c) by curtailing very little active power in Fig. 19(b). Conv. PQ remains trapped at the $P_{pv} = 0$ point.

The voltage set point V_{ref} becomes infeasible again in t_4, when all four methods behave much like during t_2. This transition shows that the two hill-climbing techniques easily re-identify the voltage peak and critical P/Q ratio, and proves that they can adapt to changing conditions and targets.

Similar observations are drawn in the final phase t_5, when V_{ref} is now reduced marginally below V_{max}. Again, only the two adaptive algorithms meet the attainable target, with Adaptive PQ+ inducing much less ripple than the basic algorithm of [**?**], as shown in Table V.

B. PV Transient

In order to further validate the effectiveness of the proposed technique, the PV power is changed in ramp like manner as shown in Fig. 20 (a). In nominal condition, P_{pv} is set to 600 W. After t_1 duration it is decreased at a rate of 60 W/s until it settled at 300 W. After t_2 duration it is further increased at the same rate, and finally it settles at 480 W in t_3. Inverter node voltage corresponds to this P_{pv} profile when voltage regulation functionality is disabled is shown in Fig. 20 (b). The instantaneous inverter current and voltage waveform is shown in Fig. 21. For this case also, the proposed Adaptive PQ+ technique is compared with other three alternatives. Fig. 22 shows the reactive active power, and inverter node voltage for all the four methods.

Fig. 22: Experimental results for the four study-case methods under PV transients: (a) Reactive power profile, (b) Active power profile, (c) PV node voltage profile

In the first phase t_1, all the techniques regulate the inverter voltage V_{fil} to the reference value (Fig. 22 (c), black dotted line). However, the steady-state ripple values are different with all the techniques and so is short term voltage flicker. Table VI shows the P_{st} values in t_1 duration with all the techniques. Although P_{st} values are well within the maximum allowable limit ($P_{st} < 1.0$) with all the techniques, it is higher for adaptive PQ algorithm.

At the end of t_1 interval, P_{pv} is reduced at a rate of 60 W/s, until it settles at 300 W, rendering V_{ref} infeasible as shown in Fig. 22 (b) and (c) respectively. Conv. Q offers suboptimal voltage regulation, as reactive power alone cannot guarantee maximum possible voltage regulation. Conv. PQ technique, as expected, touches the V_{max} point and quickly overtakes it , and settles to a much lower value due to massive active power curtailment, as shown in Fig. 22 (c). Both the adaptive algorithms achieve V_{max} point in this duration, as shown in Fig. 22 (c). However, the voltage oscillation is visibly higher and the P_{st} level with the basic adaptive algorithm is higher than proposed adaptive algorithm. It is wort noting that the amount of active power curtailment with these two adaptive techniques are very much less as shown in Fig. 22 (b). Some times the P_{pv} (Fig. 22 (b) green and purple solid lines) with these techniques almost coincide with P_{pv} of Conv. Q (Fig. 22 (b) Blue solid line). However, the adaptive techniques able to achieve V_{max} point while the Conv. Q techniques regulates the voltage to a lower value.

In the final t_3 duration, P_{pv} is increased at a rate of 60 W/s , until it reaches 480 W. This makes V_{ref} again feasible to achieve as shown in fig. 22 (c) (black dotted line). Due to the massive active power curtailment, V_{fil} continues to lock at a lower value with Conv. PQ technique (Fig. 22 (c), Orange line). However, all the other techniques regulate the V_{fil} to its reference value V_{ref}, with different flicker levels

The consolidated experimental results are given in Table. V for load transient and in Table. VI for the PV transient. The experiments confirm the main conclusions from the simulations analysis: Conv. Q delivers a stable output, but it cannot

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TABLE VI: Comparison of Voltage Regulation Performance

Duration	$\mathrm{V_{ref}}$	$\mathrm{V_{max}}$	Steady-state value of V_{fil} (pu)				Steady-state voltage ripple (%)				Short term voltage flicker (P_{st})			
	pu	pu	a	b	c	d	a	b	c	d	a	b	c	d
t_1	**1.01**	1.06	**1.01**	**1.01**	**1.01**	**1.01**	0.10	0.15	1.78	0.69	0.3747	0.3747	0.5977	0.4425
t_2	1.01	**0.0.97**	0.0.96	0.91	**0.97**	**0.97**	0.28	0.38	7.2	1.54	0.3658	0.3628	1.1393	0.8572
t_3	**1.01**	1.05	**1.01**	0.91	**1.01**	**1.01**	0.18	0.38	1.58	0.54	0.4442	0.3628	0.6538	0.4647

a= Conventional Q, b= Conventional PQ, c= Adaptive PQ [**?**], d= Adaptive PQ+

achieve the maximum possible voltage under heavy undervoltage conditions; Conv. PQ is prone to instabilities and may require manual intervention to restore normal operation once converged to a $P_{pv} = 0$ point; the two adaptive algorithms always yield the best possible voltage outcome, i.e. the lowest between V_{ref} or V_{max}.

In terms of P_{st}, in case of load transient [**?**] yields comparatively higher value of P_{st} compared to its alternatives as given in Table V. However, in this case study the P_{st} value always remain within the maximum allowable limit (<1.0) with all the regulation techniques. On the other hand the variable step mechanism in Adaptive PQ+ mitigates this issue to a large extent, exhibiting a much more consistent ripple behavior. Therefore, with this technique the P_{st} value reduced significantly. In case of variation in PV power, the P_{st} value is even higher with basic adaptive strategy [**?**] compared to the former case. As can be seen from Table VI the P_{st} value exceeds the limit during t_2 interval. Wherein, the proposed Adaptive PQ+ in this case study also able to restrict the P_{st} value within the maximum allowable value. This shows that the proposed Adaptive PQ+ is able to maintain a balance between voltage regulation and power quality for this particular experimental set-up.

VI. CONCLUSION

This paper shows that the conventional Q voltage regulation method is limited by the reactive power capacity of the inverter and may results in undesired tripping at higher voltage condition. Conventional PQ linear control methods are not constraint by that limitation, but pose serious risks for instability in case the voltage set point becomes infeasible even momentarily, a condition not impossible in a network with highly varying power flows. The proposed adaptive method bridges this gap by adopting a hill-climbing approach. Simulations and experiments on a hardware prototype validate that this method leverages both active and reactive power inverter capacity and successfully handles the non-monotonic characteristic. The unavoidable side-effect of induced ripple and consequently the short term voltage flicker (P_{st}) due to the step-like operation is deemed acceptable due to the variable step mechanism proposed in this paper. In fact, it is found to be only slightly higher than the measurement noise in the experiments, which indicates a good balance between voltage regulation efficacy and power quality.

The network-agnostic and reliable nature of the proposed method renders it useful for PV systems and other IBRs connected to medium and low voltage distribution networks. This study has treated this topic from the perspective of closed-loop voltage regulation; future work involves developing a $P-Q-V$ droop method to tackle the non-monotonicity problem for power-sharing applications of several IBRs connected on the same node.

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This article has been accepted for publication in IEEE Transactions on Industry Applications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TIA.2022.3180280

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