Why Distributed Inverter Control is Important

World's trend toward Renewable Energy (RE) due to global warming and low cost of renewables led countries around the world to switch from fossil fuel to RE resources. This change has significant effect in electrical distribution networks due to integration of RE Distributed Energy Resources (DER) such as wind and solar in generation sector and Electric vehicles (EVs) charging stations in the load sector respectively, which will likely affect grid voltage profiles and cause voltage violations in the network [1].

This challenges Distribution System Operators (DSOs) to new grid issues such as voltage violations, thermal overloading of components, e.t.c. These problems limit Integration of further EVs and or DERs in the grid [2]. Among these problems, [3] voltage violation is the most critical one, and DSOs goal is to minimize voltage violation in order to have more room for further integrations, while maintaining the power quality and reliability of the grid stable. Distributed inverter control is one of the modern and efficient techniques to avoid voltage violations. This control technique provides a potential solution to mitigate the mentioned issues and defer investment costs on upgrading the network infrastructures. Therefore, integration of inverter control strategies in PyPSA would be on one hand an interesting feature and on the other hand a useful tool for PyPSA users in this field.

Inverters are semi-conductor devices and are used for conversion of Direct Current DC to Alternate Current AC, traditionally under unity power factor. But inverters can operate under any power factor by changing the phase angle between their voltage and current outputs using the power electronic devices [4]. This characteristic enables DER inverters and EV chargers to support the grid in terms of reactive power compensation under the chosen control type to bring the voltage back to the predetermined allowed range [5]. Inverter reactive power capacity can be flexible and provide both capacitive and inductive reactive power support based on grid need and type of control strategy [6].

Equation 1 [7] below is used for reactive power calculation in each controller, where "p_set" is the amount of generated power and "power factor" is the ratio between active and apparent power of the connected inverter. According to this equation, reactive power compensation is only available when there is generation, as depicted in figure 1a.

$$q = \mathrm{p\_set} \times \tan(cos^{-1}(\mathrm{power\_factor})) \qquad (1)$$

Fix power factor Control (fixed_cosphi)

According to reference [7, 8] in this strategy, the power factor of the inverter is fixed to a value usually based on agreement between power producer and Distribution System Operator under regulatory framework, therefore a fixed amount of reactive power will compensated for each generation amount (p_set) per snapshot, and q is the controller reactive power output calculated from equation 1. Figure 1a and 1b depicts the behavior of reactive power compensation for this strategy.

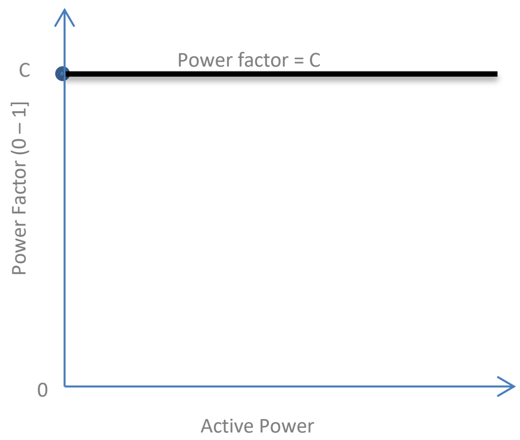


Figure 1a: Schematic of fix power factor control

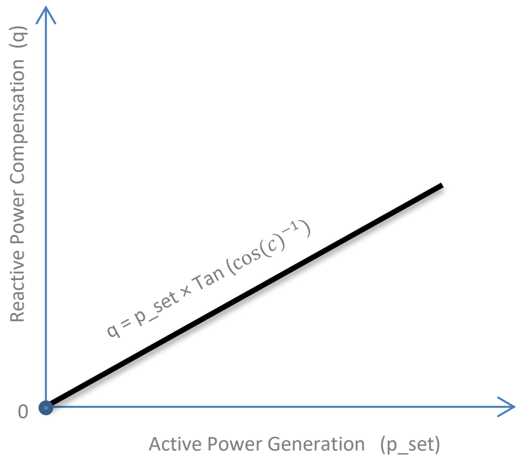


Figure 1b: Reactive power output as active power generation increases

New introduced attributes In PyPSA:

- **S_nom:** Inverter apparent power
- **Power_factor**: The ratio of active power "p_set" to the apparent power "s_nom" of the inverter.

The newly introduced attribute "power factor" together with "p_set" is used to calculate the amount of reactive power of the controller using equation 1. From figure 1b, it is clear that reactive power increases as active power generation increases; therefore, "s_nom" is used to limit the amount of reactive power compensation based on inverter capacity (s_nom), for more info read [controller reactive power compensation limit](#).

Power Factor as Function of Active Power Control (cosphi_p)

According to reference [3], [8], [7] This method is different from the fixed power factor "cosphi" method, in terms that it considers the variable of generated active power and determines the power factor accordingly. This control method avoids reactive power overcompensation from the inverters in conditions when active power generation is low since subsequent effect of voltage rise will also be below. Therefore this controller uses a reference point "p_ref (MW)" together with two other set points "set_p1 (%)" and "set_p2 (%)" to choose a reasonable power factor value for reactive power calculation. Therefore the droop curve for this controller is divided in to three zones as shown in figure 2. The choices and conditions of selecting power factor in each zone are shown in table 1 below.

	Conditions	Power factor calculation	
Power Factor	$\frac{\text{p\_set}}{\text{p\_ref}} \times 100 < set\_p1$	1	(Zone 1)
	$\text{set\_p1} \leq \frac{\text{p\_set}}{\text{p\_ref}} \times 100 \leq set\_p2$	$1 - \left(\frac{1-power\_factor\_min}{set\_p2-set\_p1} \times \left(\frac{p\_set}{p\_ref} - set\_p1\right)\right)$	(Zone 2)
	$\frac{\text{p\_set}}{\text{p\_ref}} \times 100 > set\_p2$	Power_factor_min	(Zone 3)

Table 1: Formulas for power factor as a function of active power control strategy droop curve

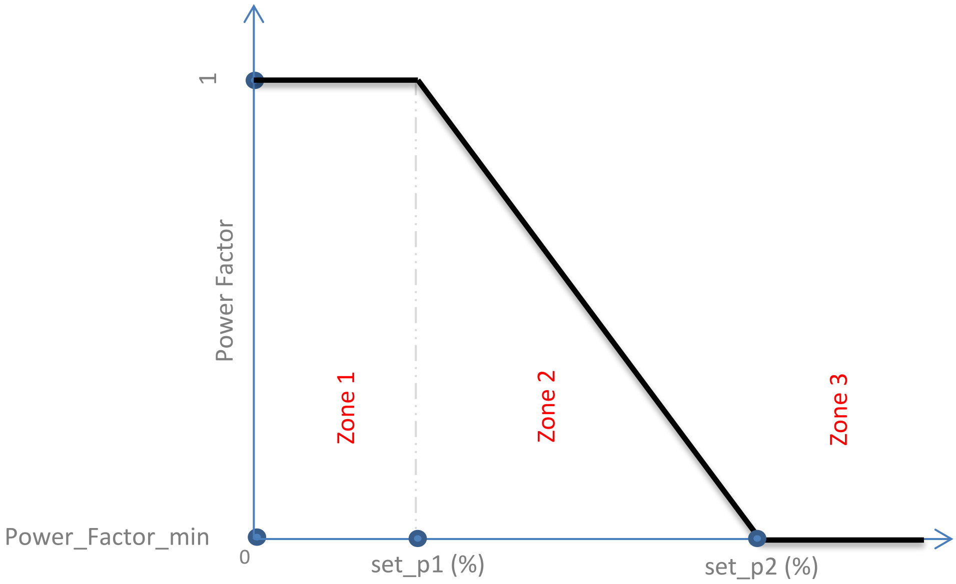


Figure 2: Power factor as a function of active power droop characteristic

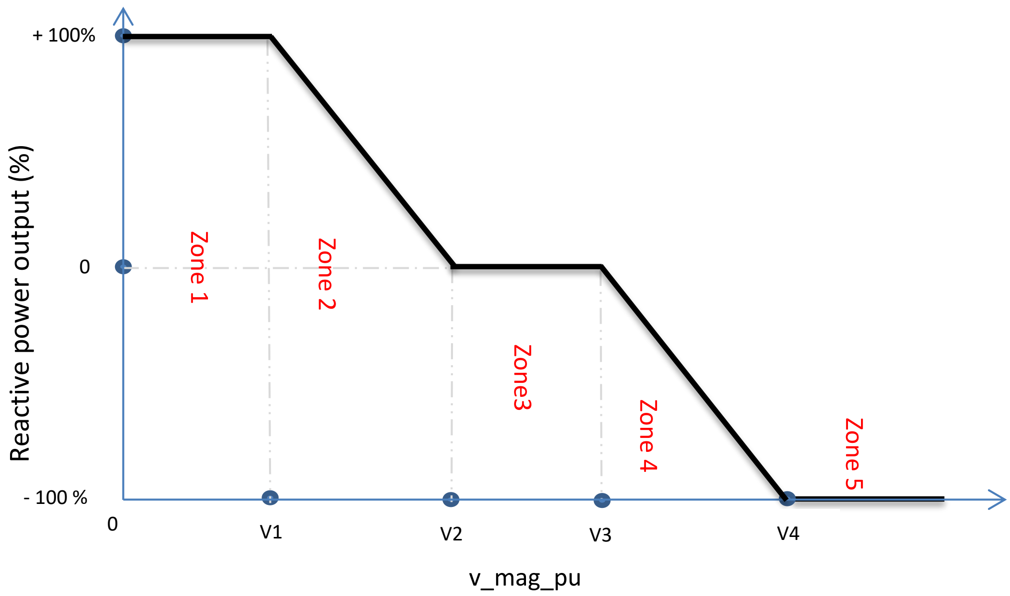
Controller calculates p_set / p_ref ×100 and check the result on controller droop curve in figure 2, based on which zone the result occurs, controller calculates the power factor of that zone as in table 1 and then calculates the amount reactive power compensation based on the calculated power factor from equation 1 as the controller output. Therefore, this controller sets the reactive power and power factor values in n.component_t.q and n.component_t.power_factor, respectively.

New introduced attributes In PyPSA:

- Set_p1: a set point in percentage (see figure 2)
- Set_p2: a set point in percentage (see figure 2)
- S_nom: inverter apparent power, it is used to make sure that sum of active and reactive power $\sqrt{p\_set^2 + q^2}$ is not exceeding inverter capacity "s_nom".
- power_factor_min: minimum power factor that controller will work if p_set / p_ref*100 is greater than set_p2 (see figure 2).
- P_ref: a reference point for controller where controller decides the power factor choice based on p_ref and p_set (see figure 2).

Reactive power as function of voltage Control (q_v):

According to (7), (3)This inverter control method utilizes its available amount reactive power very efficiently than the other two controllers when it comes to reactive power compensation, such that it provides reactive power support based on voltage information of the bus where this inverter is connected, this way it avoids unnecessary reactive power compensations. For this purpose the droop characteristic for reactive power calculation for this controller is divided in to 5 zones as shown in figure 3. Reactive power calculation formulas, conditions and choices are shown in table 2.



Reactive power output in percentage	Conditions (per unit)	Reactive power (%)	Zones
	v_pu _bus < v1	100	Zone 1
	v1 =< v_pu_bus = < v2	$100 - (\frac{100}{v2-v1})(\text{v\_pu\_bus} - v1)$	Zone 2
	v2 < v_pu_bus <= v3	0	Zone 3
	v3 < v_pu_bus < = v4	$-(\frac{100}{v4-v3})(\text{v\_pu\_bus} - v3)$	Zone 4
	v_pu_bus > v4	-100	Zone 5

Table 2: Droop characteristic formulas for reactive power as a function of voltage controller

Controller checks the location of the voltage information of the bus on its droop cure (figure 3) and provides a reactive power support in percentage from table 2. Then using equation 1 the reactive power output of this controller is calculated as in equation 2 as follow:

$$q = \text{p\_set} \times \tan(cos^{-1}(\text{power}_{\text{factor}})) \times \text{Reactive power (\%)} \times \text{damper} \qquad (2)$$

New introduced attributes In PyPSA:

- **v1, v2, v3, v4:** They are voltage magnitude set points in the order of v1 < v2 < v3 < v4 and form the controller droop characteristic curve as shown in figure 4. They form 5 zones where controller compensates differently for each zone. The reactive power calculation for each zone is shown in table 2.
- **Power_factor**: The ratio of active power "p_set" to the apparent power "s_nom" of the inverter.

- **Damper:** A constant multiplied to the output of the controller; it will be needed when controller does not converge due to voltage difference outer loop condition (x_tol_outer) It takes values greater than zero up to 1.
- **S_nom:** Inverter apparent power, which is already introduced by fixed power factor method, this attribute will also be used in "q_v" controller to limit reactive power compensation limit for more info read controller reactive power compensation limit.

Controller Reactive Power Compensation Limit

Inverter maximum available reactive power compensation is calculated using equation 3 as follow:

$$q\_available = \sqrt{s\_nom^2 - p\_set^2}) \tag{3}$$

Where "s_nom" is inverter apparent power capacity and "p_set" is the generated power. For reactive power compensation controllers use equation 1 which is as a function of active power generation, therefore sometimes when generation or "p_set" is maximum, according to equation 3 q_available reduces, in this case inverter fails to fulfil reactive power need because inverter capacity "s_nom" as in equation 4 does not allow it.

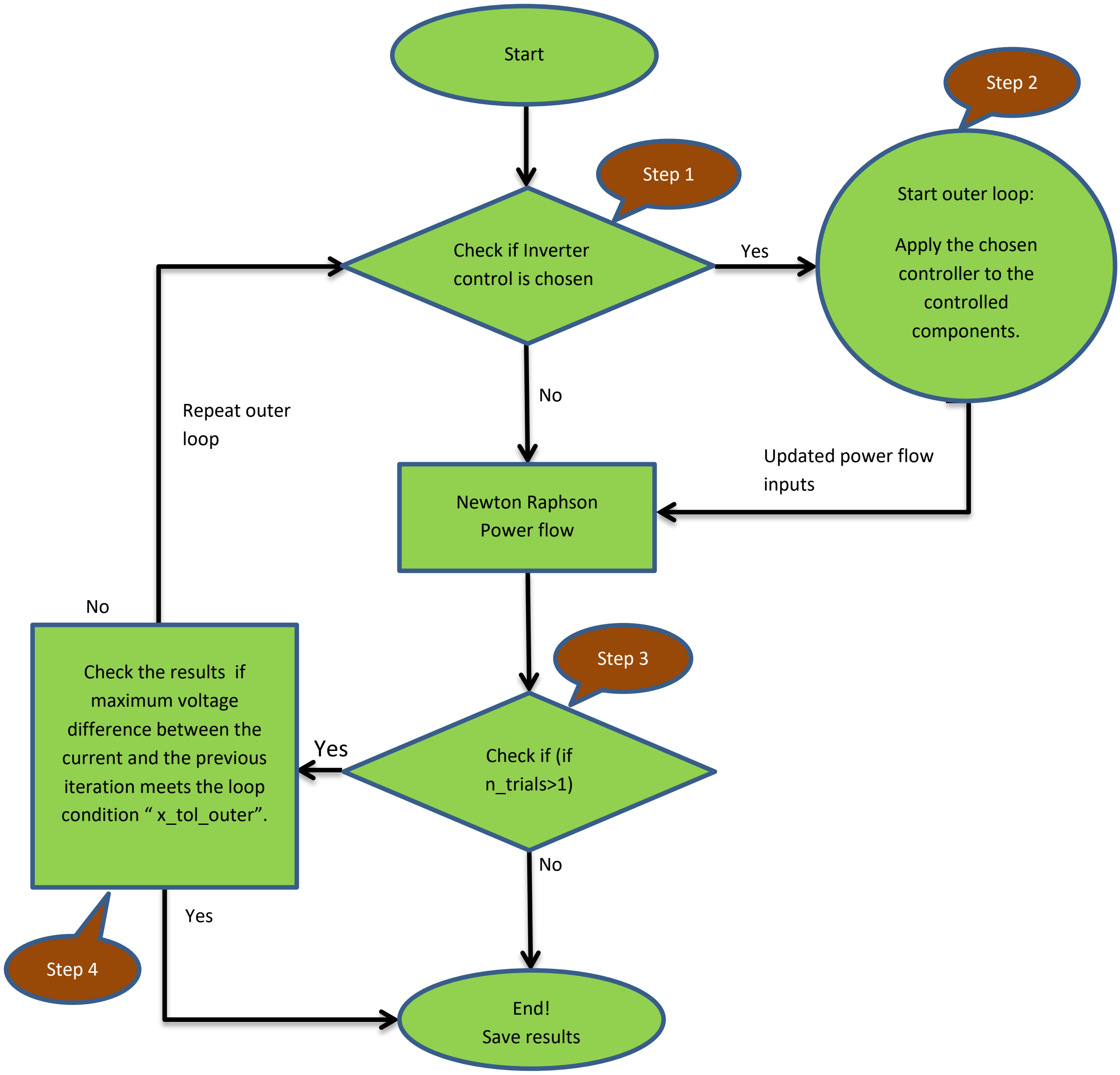
$$S\_nom = \sqrt{p\_set^2 + q\_available^2} \tag{4}$$

In this case as solution controller reduces p_set to fulfil reactive power need and saves the final result $p_{set} = \sqrt{s\_nom^2 - q^2}$ to n.component_t.p or q data frames. But p_set reduction is limited by the provided power factor, the minimum value that p_set can take is determined by equation 5

$$p\_set = s\_nom \times power\_factor \tag{5}$$

Note: This behavior "reduction of p_set to fulfill reactive power need" is followed from CERBERUS software and is only for fixe power factor and reactive power as a function active power control strategies.

Power flow loop description in four steps



Steps for outer loop:

Step 1: Outer loop which contains application of control strategies activates, when inverter_control is "True" (defaults to False) in n.pf (inverter_control = False). Outer loop applies the chosen control strategy on the chosen components and updates the network.

Step 2: In this step the power flow is run after application of control strategies on the network.

Step 3: n_trial_max is the number of power flow repetition per snapshot. It has a value of 30 trials when the type of control strategy is "q_v" and 1 for other controllers. "q_v" is a voltage dependent controller and to avoid voltage fluctuations due to reactive power compensation there is a voltage tolerance limit between the two consecutive iterations. This tolerance within the power flow loop is called "x_tol_outer". In each power flow the maximum "v_mag_pu" difference of the current iteration and the previous iteration is compared with the x_tol_outer limit. If voltage difference is less than or equal to x_tol_outer, power flow will converge, otherwise it will keep iterating up to 30 iterations. In the worst-case scenarios when it did not converge, as solution "damper" attribute is introduced which is directly multiplied to the controller output and takes values (0, 1]. Damper values less than 1 will help controller from big swings and finally lead it to converge. Another solution is changing the parameters (v1, v2, v3, v4, power_factor).

Step 4: calculate the voltage difference of previous iteration and the current iteration and compare the result with the x_tol_outer, if the voltage difference is equal or less than x_tol_outer, the condition is met, and the power flow ends here. If not repeat (maximum of 30 iterations) the power flow with the outer loop again until the mentioned condition is met.

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