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Published in:
IEEE Access

Link to article, DOI:
10.1109/ACCESS.2020.3005094

Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Sarkar, M., Souxes, T., Hansen, A. D., Sørensen, P. E., & Vournas, C. D. (2020). Enhanced Wind Power Plant Control Strategy during Stressed Voltage Conditions. IEEE Access, 8, 120025-120035. https://doi.org/10.1109/ACCESS.2020.3005094
Enhanced Wind Power Plant Control Strategy During Stressed Voltage Conditions

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This work was supported by the Security Assessment of Renewable Power Systems (SARP) Project funded by Energinet through the Public Service Obligation Scheme under Grant 12427 (Forskel).

ABSTRACT Increasing renewable energy sources in power system has brought forth many challenges in terms of power system stability, one of which is voltage stability. Preventive and corrective actions to alleviate voltage instability are mainly developed for traditional power systems without high share of renewables. This article aims to assess the reactive power based voltage support from wind power plants under stressed voltage conditions. Firstly, the performances of the conventional wind power plant control strategies applied during stressed voltage conditions are studied. A novel enhanced wind power plant control strategy is developed, which increases wind power plant reactive power capability through control of wind power plant tap changing transformer. Performance of this novel strategy is compared and evaluated against the conventional wind power plant control strategies applied during the stressed voltage conditions. Results show that the developed control strategy helps in alleviating voltage instability 5% more effectively when compared to the conventional WPP control strategies applied during stressed voltage conditions. The developed control strategy is implemented and simulated in a snapshot of the Hellenic power system to verify the implementation feasibility and effectiveness in a real large power system.

INDEX TERMS Control strategies, reactive power support, stress conditions, voltage stability, voltage support, wind power, wind power plant.

I. INTRODUCTION Environmental concerns due to fossil fuel based generations coupled with reducing prices of renewable energy source (RES) based generations have paved the way for increased share of RES (like wind power plants (WPP)) [1] in power systems all over the world. In 2018, wind energy was the second largest form of power generation capacity in EU with installed capacity of 178.8 GW [2]. Due to increasing penetration of RES generations, additional challenges towards secure and stable operation of power system has evolved. Maintaining voltage stability of power system is one of the major challenges [3]. When the power system changes from normal to alert state due to some n-1 contingency, there are preventive operational measures specified to mitigate the risk of voltage instability in the system [4] as shown in Fig. 1. The specified preventive actions have mainly been devised for traditional power systems. However, with large share of WPPs in the power system, preventive actions from WPPs can be essentially required. The main focus of this article is to explore preventive support capabilities of WPP through reactive power/voltage control possibilities from WPP under stressed voltage conditions to prevent voltage based emergencies.

Synchronous generators have been traditional sources of reactive power in conventional power systems [5], [6]. Various studies have shown that by replacing these synchronous generators with converter connected RES generators, voltage stability margin of the power system reduces due to reduced reactive power availability in the system [7]. To mitigate this, on one hand, auxiliary reactive power sources, such as STATCOMs or Static Var Compensators (SVCs) could be used, which is expensive. On other hand, reactive power capability of installed RES could be utilised, which is gaining extra
importance with replacement of conventional synchronous generators with converter connected RES [8], [9].

Voltage ranges for normal and alert state as well as requirements during alert state varies in different grid codes. Table 1 shows overview of grid code requirements during alert state in some of the networks around the world (mostly in 400 kV networks). Some grid codes, like Irish grid code [10] and North American Reliability Corporation (NERC) grid code [6], do not specify alert voltage ranges and corresponding requirements during alert state. European Commission recommends WPPs to stay connected and continue operation for up to 60 mins during alert state in Continental Europe [11]. In Nordic [12] and UK [13] network codes only high voltage ranges for alert state are defined, where WPP is expected to stay connected and continue operation for the time period defined. If the voltage at the WPP point of connection remains below alert voltage range (or normal voltage range in Irish and NERC grid codes) for certain time period, typically 1.5 to 3 sec (fault ride-through mode), WPPs are allowed to disconnect. However, none of the grid codes have specific control actions prescribed for WPPs during alert conditions.

One of the first reactive power control function requirement from WPP has been unity power factor control, which implies that there is no exchange of reactive power from WPP to the grid [14]. However, with increasing penetration of WPPs, reactive power and voltage requirements (both dynamic and steady-state) from large utility-scale WPPs have been tightened. Different WPP control modes are specified in grid codes [11], [12], [15]. EU network code on requirements for grid connection of generators states that WPPs should be capable of providing reactive power by either voltage (V) control, reactive power (Q) control or power factor control during steady-state operation [11]. All three control modes are mutually exclusive. WPP controller should be able to receive and accomplish specific set-points ordered by transmission system operators (TSO) in agreement with WPP operators [12].

In V control mode, WPPs should be capable of controlling voltage control at the Point of Connection (PoC) through reactive power exchange with the network. According to EU network codes [11], WPPs should be capable of voltage control at the PoC with voltage ranging from 0.95 pu to 1.05 pu, with or without a deadband ranging from zero to ±5% of reference 1 pu network voltage. WPPs must be capable of performing the control within its dynamic range and voltage limits with the droop configured [12]. When more than one WPP are connected to the grid at the same Point of Common Coupling (PCC), droop control is used to ensure stable and co-ordinated voltage control of WPPs. Each WPP provides reactive power support in response to PCC voltage drop proportional to their droop setting. Droop values recommended by Danish TSO Energinet ranges between 2%-7% [12]. In Q control mode, WPP should be able to control the reactive power at the PoC to a reactive power set-point. The set-point can be anywhere in the reactive power range as per the grid code requirements. Power factor control mode requires WPPs to control reactive power proportionately to the active power at the PoC, according to power factor set-point which is set within the reactive power range of the capability. These conventional control strategies are mainly been studied either for normal operation or for transient voltage dip conditions, that is, fault ride-through mode [16]–[20]. However, how the WPP should react in alert state (long-term stressed voltage conditions) has not been addressed in literature. Long-term voltage stability phenomena evolve in the time scale of several tens of seconds to a few minutes as defined in [21]. This article focuses on WPP control strategies during long-term stressed voltage conditions.

The objective of this article is to quantify the WPP support capabilities during long-term stressed voltage conditions. Performances of the WPP control strategies are evaluated in terms of improved voltage profile and maximum power transfer capability (MPT). The main contributions of this article are:

### TABLE 1. Overview of grid code voltage requirements during alert state.

| Network   | Normal operation [pu] | Alert operation [pu] | Requirements during alert state | Unmet needs |
|-----------|------------------------|----------------------|---------------------------------|-------------|
| Continental Europe [11] | 0.9 to 1.05 | 0.85 to 0.9 | Stay connected and continue operation for 60 mins | No specific control action during alert condition is mentioned |
| Nordic [12] | 0.9 to 1.05 | 1.05 to 1.1 | Stay connected and continue operation for 20 ≤ t ≤ 60 mins |
| Baltic [11] | 0.9 to 1.097 | 0.88 to 0.9 | Stay connected and continue operation for t ≤ 60 mins |
| UK [13] | 0.9 to 1.05 | 1.05 to 1.1 | Stay connected and continue operation for 20 mins |
| Ireland [10] | 0.9 to 1.05 | Not specified | Not specified |
| NERC [6] | 0.9 to 1.1 | Not specified | Not specified |
a) Comparison and sensitivity study of conventional WPP control strategies when applied during stressed voltage conditions;

b) Development of a novel enhanced reactive power capability based WPP control strategy whose efficacy is compared against conventional WPP control strategies;

c) Validation of effectiveness of the control strategies in a large simulated power system - Hellenic Interconnected System (HIS).

This article is organised as follows: Section II describes the WPP model, as well as, both the simple 3-bus power system model and HIS model used in the study. Section III describes the conventional WPP strategies applied during stressed voltage conditions. Section IV describes the proposed enhanced reactive power capability based WPP control strategy. Results are presented and discussed in Section V. Section VI concludes the paper.

II. SYSTEM MODELLING

A. WIND POWER PLANT MODEL

In this study, an aggregated WPP model is derived for a 210 MW WPP consisting of 91 Type 4 WTs each of 2.3 MW. In the WPP layout, depicted in Fig. 2, which is similar to the Horns Rev 2 layout, the cable parameters are based on the data given in [22]. WPP array voltage is 33 kV. Distances between WTs and to substation (in km) are indicated by the numbers in red. All WTs on a string are spaced equidistant. Distance between two adjacent string is equal.

The power collection system is aggregated based on the methodology proposed in [23]. Single line diagram of the aggregated WPP model is shown in Fig. 3. It consists of a single WT together with equivalent impedance and susceptance of aggregated power collection system. Aggregated WPP parameters are given in Table 2. More details on these parameters can be found in authors’ previous work [24].

The WT model is based on Type 4A WT model as defined by IEC standard 61400-27-1 [25], [26]. Type 4 WTs are variable speed WTs with the generator connected to the grid through a full scale power converter [25]. IEC standard 61400-27-1 specifies two Type 4 models; Type 4A model neglects the aerodynamic and mechanical parts whereas Type 4B model includes a 2-mass mechanical model [25]. In Type 4 WTs, active and reactive power control are mutually independent. However, it should be mentioned that, following the limitations imposed by the size of the WT grid side converter, the WPP reactive power capability depends on the active power production and grid voltage. In [24], authors have shown that the reactive power capability of WPP is either voltage or current limited depending on converter parameters and operating conditions. The converter voltage limited reactive power, $Q_V$ and converter current limited reactive power, $Q_I$ at the WPP side of the WPP transformer (TRWP) can be expressed as in (1) and (2) respectively [24].

$$Q_V = \sqrt{\left(\frac{V_{WPP}V_C}{Z_{eq}}\right)^2 - \left(P_{WPP} + \frac{V_{WPP}^2 R_{eq}}{|Z_{eq}|^2}\right)^2}$$

$$Q_I = \sqrt{\left(V_{WPP}I_{C}^{\max}\right)^2 - P_{WPP}^2}$$

where,

- $V_{WPP}$ = grid voltage at point of connection of WPP
- $V_C$ = maximum allowable converter voltage ($V_C = V_C^{\max}$, for maximum injection capability; $V_C = V_C^{\min}$, for maximum absorption capability)
- $I_{C}^{\max}$ = maximum allowable converter current
- $P_{WPP}$ = active power production from WPP
- $Z_{eq}$ = $R_{eq} + jX_{eq}$, sum of impedance of aggregated collection system cables, individual WTs and WT transformers

![FIGURE 2. Layout of 210 MW WPP. Numbers in red depict distances in km.](image)

![FIGURE 3. Aggregated WPP model [24].](image)

| Parameter | Description | Value [pu] |
|-----------|-------------|-----------|
| $I_{C}^{\max}$ | Maximum converter current | 1.25 |
| $V_{C}^{\max}$ | Maximum converter voltage | 1.1 |
| $V_{C}^{\min}$ | Minimum converter voltage | 0.8 |
| $Z_{eq}$ | Equivalent impedance of Horns Rev 2 power collection system | 0.0144+j0.1446 |
| $B_{eq}$ | Equivalent susceptance of Horns Rev 2 power collection system | 0.0211 |

The WT model is based on Type 4A WT model as defined by IEC standard 61400-27-1 [25], [26]. Type 4 WTs are variable speed WTs with the generator connected to the grid through a full scale power converter [25]. IEC standard
Furthermore, the maximum reactive power injection and absorption capability of WPP can be expressed as in (3) and (4), respectively.

\[
\begin{align*}
Q_{\text{inj}}^{\text{max}} &= \min(Q_V, Q_I) + B_{eq}V_W^{2} \quad (3) \\
Q_{\text{abs}}^{\text{max}} &= \max(Q_V, Q_I) + B_{eq}V_W^{2} \quad (4)
\end{align*}
\]

where,

\[ B_{eq} = \text{equivalent shunt susceptance of collection system cables} \]

Fig. 4 illustrates WPP reactive power capability characteristics for different voltage levels. In Fig. 4, solid and dotted lines represent WPP reactive power injection and absorption capabilities respectively. Notice that, as expected, when the voltage at WPP connection point is maintained constant by the LTC, reactive power capability of WPP reduces with the increase in wind power production.

\[ P_L = P_0 \left( \frac{V_L}{V_0} \right)^2; \quad Q_L = Q_0 \left( \frac{V_L}{V_0} \right)^2 \quad (5) \]

where,

\[ V_0 = \text{reference voltage} \]
\[ P_0 = \text{nominal active load at reference } V_0 \]
\[ Q_0 = \text{nominal reactive load at reference } V_0 \]

Stressed voltage conditions are emulated by gradually increasing the nominal load, \( P_0 \), assuming unity load power factor. The WPP is assumed to produce constant active power of 0.6 pu (on WPP base).

**C. HELLenic INTERCONNECTED SYSTEM MODEL**

In the 3-bus power system model, other reactive power sources are not considered which would typically be available in a large power system. Therefore, HIS [9], [27] based on a snapshot provided by the Independent Power Transmission Operator (IPTO) to the research team of NTUA in the framework of the research program [28] is modelled for this study. It consists of 1245 buses, 43 generators, 920 lines, 528 LTC transformers and 75 WPPs. The Peloponnese area in the HIS has been found to be insecure by on-line Voltage Security Assessment [29] for a specific snapshot and contingency of Summer 2010. In this paper, a 36 MW WPP in the Peloponnese area is modelled to provide reactive power support in accordance with the different control strategies, which are discussed in Section III and Section IV. Reactive power from other WPPs in the system are not controlled. The snapshot of HIS analysed in this article corresponds to the operating conditions as on 1 December 2017 with total load of 5650 MW of which 442 MW is connected in the Peloponnese area. The system has been modelled in MATPOWER and quasi-steady state simulations have been performed.

**D. ASSUMPTIONS**

Assumptions for this study are:

- To emphasise on the WPP support capabilities during stressed voltage conditions, the WPP are operated at unity power factor (zero reactive power exchange) during normal voltage ranges. This assumption arises from...
economic perspective that WPP will incur additional losses to provide reactive power support during normal state. However, there can be specific cases based on grid requirements where WPPs are required to provide reactive power or voltage support even during normal state. A deadband of is used for all WPP control strategies to ensure WPP provides reactive power support only during stressed voltage conditions.

- Fault ride-through operation of WPP is not simulated, that is, the WPPs remain connected to the grid at voltages below alert (or normal) operation range. This allows for computation of MPT of the network and is a traditional practice for voltage stability studies.
- A quasi-steady state control has been implemented using MATPOWER. Fast control dynamics, like PI controllers, have been neglected, to reduce computational complexity for large power systems.

### III. CONVENTIONAL CONTROL STRATEGIES

The conventional WPP voltage/var control strategies as required by grid codes can be of three types, (i) Q control, (ii) Droop control and (iii) V control. All these strategies aim to maintain reactive power exchange or voltage at PCC \( V_{PCC} \). In this article, all three conventional WPP control strategies are applied during stressed voltage conditions.

As mentioned previously, the voltage at the WPP side is maintained by the LTC actions of TRWP (which is controlled by the TSO in some countries, like Denmark [12]). In this case, the WPP controller is required to be capable of controlling the reactive power supplied by WPP at the PoC. The WPP controller does not control the voltage set-points of the LTC. The voltage at PCC, \( V_{PCC} \), is monitored to detect the stress condition, based on the threshold voltage (predefined by the TSO). When \( V_{PCC} \) falls below the threshold voltage, \( V_{th} \) WPP supports the grid voltage through reactive power contribution. In this study \( V_{th} \) is chosen as 0.95 pu.

#### A. Q CONTROL

The Q control strategy applied during stressed voltage condition, aims to provide reactive power as illustrated in the flowchart shown in Fig. 6. Based on the system conditions, reactive power reference, \( Q_{PCC}^{calc} \) is obtained externally (from TSO). The Q control strategy calculates the reactive power losses in the TRWP to obtain the reactive power reference at the PoC, \( Q_{WPP}^{calc} \). Depending on current operating conditions, \( P_{WPP} \) and \( V_{WPP} \), reactive power capability limit of WPP, \( Q_{max}^{inj} \), is calculated using (3). Based on \( Q_{WPP}^{calc} \) and \( Q_{max}^{inj} \), \( Q_{WPP}^{ref} \) is calculated using (6) and is sent to WPP controller.

\[
Q_{WPP}^{ref} = \begin{cases} 
Q_{max}^{inj} & \text{when } Q_{WPP}^{calc} > Q_{max}^{inj}, \\
Q_{WPP}^{calc} & \text{otherwise} 
\end{cases}
\]  

#### B. DROOP CONTROL

Droop or slope voltage control strategy aims at controlling \( V_{PCC} \) by providing reactive power according to pre-defined Q-V droop curve. Fig. 7 illustrates the applied droop curves for droop, \( R \) of 4%, 6% and 8%. The deadband included in the droop curve ensures that reactive power support from WPP is obtained when the grid voltage is below the pre-defined threshold voltage denoting stress conditions. Lower droop value results in increased WPP support which is defined by (7).

\[
Q_{PCC}^{calc} = Q_{PCC} - \frac{1}{R} (V_{PCC} - V_{th}) \quad (7)
\]

The flowchart describing droop control strategy applied during stressed voltage conditions is shown in Fig. 8. The applied droop control strategy is similar to the Q control strategy, except for the reactive power at PCC, \( Q_{PCC}^{calc} \), is calculated from the Q-V droop curve.

#### C. V CONTROL STRATEGY

When a single WPP is connected at the PCC, the WPP can be operated in automatic voltage control mode without droop [6]. The V control strategy applied during stressed voltage conditions, is illustrated in Fig. 9. The WPP supports the
FIGURE 8. Droop control strategy applied during stress conditions.

grid by maintaining $V_{PCC}$ at a defined PCC voltage set-point, $V_{set}$, $Q_{calc}$ is calculated such that $|V_{PCC} - V_{set}| < \epsilon$, where $\epsilon$ is the tolerance. For dynamic simulations this is typically implemented using a PI controller. Since quasi-steady state control is in focus in this article, an iterative loop is used to reach the tolerance $\epsilon$.

IV. PROPOSED CONTROL STRATEGY

This work proposes a novel enhanced capability based V control strategy to mitigate stressed voltage conditions.

This strategy enhances WPP reactive power capability through LTC control actions to utilise maximum WPP reactive power capability. As shown in Fig. 4, WPP capability is dependent on PoC voltage, which is controlled by the LTC actions of TRWP.

Fig. 10 shows that, when WPP active power generation, $P_G$ is constant at 0.6 pu, WPP reactive power capability increases with increase in voltage from 0.9 pu to 0.93 pu. However, beyond this voltage, WPP reactive power capability decreases with increase in voltage. Below voltage of 0.93 pu, WPP reactive power is limited due to converter current limitation, while above 0.93 pu, it is limited by converter voltage limitation. Therefore, to utilise maximum WPP reactive power injection capability, PoC voltage reference, $V_{refWPP}$, can be set such that,

$$Q_{inj}^{max} = \text{sup} \left\{ Q_{inj}^{max}(P_{WPP}, V_{WPP}) \mid P_{WPP} = P_G \right\}$$

From Fig. 10, for active power generation of 0.6 pu, $V_{refWPP}$ is chosen as 0.93 pu. This $V_{refWPP}$ is maintained through LTC control. The flowchart describing the enhanced reactive power capability based voltage control strategy is shown in Fig. 11. In addition to LTC control signal, $Q_{refWPP}$ signal is generated similar to V control strategy described earlier. That is, when $V_{PCC} < V_{th}$, PCC reference voltage is set to $V_{th}$. This control strategy can easily be applied in combination with Q or droop control strategies.

Since the proposed controls refer only to stressed voltage conditions, they are expected to be activated in rare occasions and not during everyday operation. Thus, the resulting extra tap-changing operations during a year will be limited and are not expected to influence the LTC lifetime.

It should also be noted that, the proposed control strategy does not interfere with WPP active power control strategies which can operate in different control modes such as, maximum power production, delta control, balance control etc.

V. RESULTS AND DISCUSSIONS

In this article, the control strategies are assessed from system proximity to voltage collapse based on voltage stability indices (VSI) [30]. MPT based on PV curve has been used as measure of VSI. As explained in [21], the PV curves illustrate the relation between the transferred active power and the
A. SENSITIVITY STUDY OF CONVENTIONAL CONTROL STRATEGIES

In this section, results of sensitivity study of the three conventional WPP control strategies when applied during stressed voltage conditions are analysed and discussed. As mentioned earlier, the base case is chosen as unity power factor support from WPP, that is, $Q_{PCC}^{ref} = 0$.

1) Q CONTROL

Fig. 12 shows PV curves at load bus for different values of $Q_{PCC}^{ref} = 0, 0.5Q_{max}$, and $Q_{max}$. It can be observed that the MPT of the system (marked ‘x’) increases from 1.3 pu to 1.36 pu to 1.43 pu with increasing reactive power support from 0 to $0.5Q_{max}$ and $Q_{max}$, respectively.

Comparison of PCC voltage and reactive power from WPP are shown in Fig. 13. It can be observed that, with $0.5Q_{max}$ support of 0.11 pu and $Q_{max}$ support of 0.22 pu, PCC voltage improves by 2.1% and 4.2% respectively, as compared to the case of zero reactive power support. Also note the sharp change in voltage due to step increase in reactive power support, which may not be desirable. This issue is better handled with droop control strategy as described in the next section.

2) DROOP CONTROL

Fig. 14 shows $V_{PCC}$ and reactive power injected at PCC when droop control strategy is applied during stressed voltage conditions. Three different droop values, $R = 4\%$, $6\%$ and $8\%$ are used. As seen in Fig. 14, lower droop provides increased reactive power support.

At $8\%$ droop, maximum reactive power support of 0.22 pu is reached at nominal load of 1.62 pu, whereas for $6\%$ and $4\%$ droop, the same maximum reactive power support is reached at nominal loads of 1.57 pu and 1.55 pu respectively.
Since, reactive power limit is reached in all three cases; therefore, MPT of the system remain same as in case of Q control strategy with \(Q_{\text{max}}\) support, that is, 1.43 pu. However, there is no sharp change in voltage as opposed to the Q control strategy.

3) V CONTROL
PCC voltage response and reactive power from WPP for \(V_{\text{set}}\) 1 pu, 0.98 pu and 0.95 pu are shown in Fig. 15. Notice that, when \(V_{\text{set}}\) is higher than the threshold voltage \(V_{\text{th}}=0.95\) pu, there is steep increase in PCC voltage to 0.99 pu for \(V_{\text{set}}=1\) pu and 0.98 pu for \(V_{\text{set}}=0.98\) pu, which may not be desirable. On contrary, if voltage is set at the threshold voltage of 0.95 pu, PCC voltage is maintained at 0.95 pu until WPP reactive power capability limit is reached at 1.5 pu of nominal load. MPT of the system remains 1.43 pu, same as in Q control strategy with \(Q_{\text{max}}\) support.

**B. PROPOSED CONTROL STRATEGY**
In this section, results of the proposed enhanced reactive power capability based V control strategy are analysed. Fig. 16 shows voltage at TRWP, WPP reactive power and tap ratio (LTC response) for enhanced capability based V control strategy. The five depicted regions in Fig. 16 can be explained as follows:

Region I: \(V_{\text{WPP}}\) is maintained at 1 pu by the TRWP. WPP controller maintains 0 reactive power at the HV side of TRWP as \(V_{\text{PCC}} > V_{\text{th}}\). Active and reactive power from WPP are constant implying constant current from WPP. As the load increases, tap ratio is reduced in order to maintain the voltage at the MV side of TRWP to 1 pu.

Region II: In this region, \(V_{\text{PCC}}\) crosses threshold voltage \(V_{\text{th}}\) due to increase in load. Consequently, PCC voltage reference is set to \(V_{\text{set}}\) (which is equal to \(V_{\text{th}}\)). Simultaneously, MV voltage reference for LTC transformer is reduced to 0.93 pu to obtain maximum reactive power support from the WPP according to (8). This results in constant maximum reactive power capability (refer second subplot of Fig. 16). Since, reactive power is increasing with increase in load and within the maximum injection capability of WPP, voltage at MV side of TRWP is maintained at 0.93 pu through increase in tap ratio.

Region III: LTC reaches maximum tap limit. Therefore, \(V_{\text{WPP}}\) cannot be maintained at 0.93 pu resulting in increase of \(V_{\text{WPP}}\). However, since reactive power from WPP is below the maximum reactive power capability, reactive power from WPP is increased to maintain \(V_{\text{PCC}}\) at \(V_{\text{th}}\).

Region IV: Reactive power output from WPP reaches maximum capability limit. Therefore, \(V_{\text{PCC}}\) cannot be maintained at \(V_{\text{th}}\). With increase in load, \(V_{\text{PCC}}\) starts to decrease. Since, LTC is still operating at maximum tap ratio limit, \(V_{\text{WPP}}\) starts to decrease with decrease in \(V_{\text{PCC}}\). Due to decrease in \(V_{\text{WPP}}\), WPP reactive power capability increases, resulting in increase of reactive power support from WPP.

Region V: As load continues to increase, \(V_{\text{WPP}}\) reaches 0.93 pu. (reference set-point). Therefore, \(V_{\text{WPP}}\) becomes constant. Since maximum reactive power capability of WPP is reached at \(V_{\text{WPP}} = 0.93\) pu, reactive power from WPP becomes constant. \(V_{\text{PCC}}\) continues to decrease due to increasing load. This results in release of saturated tap ratio of LTC.

It should be noted that \(V_{\text{WPP}}\) is always \(\geq 0.93\) pu. This demonstrates that WPP acts as a robust reactive power source during stress conditions when using the proposed enhanced reactive power capability based voltage control strategy.

**C. COMPARISON OF PROPOSED AND CONVENTIONAL CONTROL STRATEGIES**

1) 3-BUS SYSTEM
To compare the performance of the proposed control strategy with conventional control strategies applied during stressed voltage conditions, zero reactive power support from WPP is taken as base case. PV curves at load bus for all control strategies are shown in Fig. 17.
It can be observed that MPT of the system improves to 1.5 pu in case of proposed enhanced capability based V control strategy as compared to 1.43 pu in conventional Q, V and droop control strategies and 1.3 pu for zero reactive power support. The values of MPT (red ‘x’ marks in Fig. 17) are given in Table 4. Notice that during stressed voltage conditions, WPP support can improve MPT by 15%, that is, an additional 5% improvement can be achieved from the proposed control strategy. Interestingly, system response for V control at $V_{\text{set}} = 0.95$ pu is similar to that of 4% droop.

### TABLE 4. Maximum power transfer (pu values on 500 MVA base).

| Control strategy | Base Case | Q Control | Droop Control | V Control | Enhanced cap. V control |
|------------------|-----------|-----------|---------------|-----------|-------------------------|
| Value [pu]       | 1.30      | 1.43      | 1.43          | 1.43      | 1.50                    |
| Increase [%]     | -         | 10        | 10            | 10        | 15.4                    |

2) HELLENIC INTERCONNECTED SYSTEM

This study focuses on analysing the impact of reactive power support at PCC and a bus representing the Peloponese area, since the reactive power support from only one WPP has been modelled. Load of the whole system has been increased in steps of 1% to simulate stressed voltage conditions in the system. Conventional as well proposed control strategies are investigated and the results are shown in Fig. 18.

It can be observed from Fig. 18a that best performance is obtained from the proposed enhanced capability based V control strategy. The other three conventional control strategies also help improve the voltage substantially. System responses in the HIS is similar to the control strategy responses observed in the 3-bus power system. This shows that the proposed control strategy is equally effective when applied to large power systems. Fig. 18b depicts load vs. voltage at the bus representing Peloponese area. MPT values, depicted in Table 5, derived based on Fig. 18b show that MPT increases from 732 MW (zero reactive power support) to 738 MW (for Q, V, droop control) and 742 MW (for enhanced capability based V control). Notice that this improvement is achieved through support from single 36 MW WPP. Improvement can be manifold with larger number of WPPs providing support.

### TABLE 5. Maximum power transfer for Peloponese area.

| Control strategy | Base Case | Q Control | Droop Control | V Control | Enhanced cap. V control |
|------------------|-----------|-----------|---------------|-----------|-------------------------|
| Value [MW]       | 732       | 738       | 738           | 738       | 742                     |

Both case studies show that the proposed strategy helps in alleviating voltage instability better than the conventional control strategies applied during stressed voltage conditions.

### VI. CONCLUSION

This article proposes a novel wind power plant control strategy and compares it with conventional wind power plant support capabilities during stressed voltage conditions. Sensitivity studies of the conventional wind power plant control strategies (Q, V and droop) are conducted to study their performance during stressed voltage conditions. These sensitivity studies show that the maximum power transfer of the system remain same for all three conventional WPP control strategies. This is due to limited reactive power capability of the WPP. The proposed enhanced reactive power capability based V control strategy provides an increased reactive power support to the network. Therefore, maximum power transfer of the network improves. Results have shown that the maximum power transfer of the network improves by 10% when conventional WPP control strategies are applied.
during stressed voltage conditions. An additional improvement of 5% can be achieved with the proposed enhanced reactive power capability based voltage control strategy. This helps in alleviating voltage instability better than the conventional control strategies. This article clearly demonstrates the value of wind power plant as a reactive power source during stressed voltage conditions. Furthermore, investigation of the proposed control strategy in a large realistic power system ensures feasibility and the effectiveness of the proposed strategy.

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