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# Dynamic Reactive Power From Wind Power Plant: Voltage Control Ancillary Service Support

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***Abstract*— In conventional power systems, synchronous generators have been the main source of dynamic reactive power. However, the displacement of conventional power plant by nonsynchronous generation resources such as wind power plants (WPPs) and other Renewable Energy Sources (RESs) result in diminished dynamic reactive power reserve. System operators in different countries are trying to tackle this issue by introducing dynamic reactive power reserve as a new ancillary service. In this paper, the capability of type 4 based WPP to supply/consume dynamic reactive power is explored. A centralized WPP capability based control strategy is proposed to supply dynamic reactive power from WPP. An adaptive method is proposed to dispatch the reactive power generation from Wind Turbine Generators (WTGs) in a WPP. In the presented study, wake effect and detailed WPP model are taken into consideration. The proposed strategy is implemented on a wind integrated benchmark power system developed in DIgSILENT PowerFactory platform using IEC-61400-27-1 standard model of WTG.**

***Keywords: Dynamic reactive power compensation, wind farm controller, wind turbine generator, ancillary service.***

## I. Introduction

The world has witnessed recently a fast growth of grid integration of Renewable Energy Sources (RESs) driven by fossil fuel depletion, climate change and job opportunities provided by RES industry. Such a rapid growth in RES integration has led to the decrease in online synchronous power due to RES-driven displacement of conventional power plants. Conventional power plant displacement leads to reduced dynamic reactive power reserve and deterioration in voltage stability, as synchronous generators are the primary source of dynamic reactive power [1]. To countermeasure this deficit in dynamic reactive power reserve, Transmission System Operators (TSOs) in various countries, such as Ireland, have introduced/proposed dynamic reactive power support as an ancillary service. For example, Great Britain has introduced Enhanced Reactive Power Service (ERPS) as an ancillary service [2].

On the other hand, wind power generation being the front runner in RES integration, is expected to have largest share among all the renewables due to the rapid growth of Wind Power Plant (WPP) installation [3]. Therefore, a significant proportion of wind integration increases the importance of dynamic reactive power support from a WPP. While the ability of Variable Speed WTG (VSWTG) to decouple active and reactive power offers control flexibility similar to that of a synchronous generator, the capability of WPP of the same active power rating is relatively low and depends on many other factors such as WPP capacity, WTG type, wind speed, active power generated and Point of Common Connection (PCC) voltage. To estimate the reactive power capability of WPP, the authors in [4] presented a capability estimation method of Fully Rated Converter WTG (type 4) based WPP. However, an aggregated model of WPP is used to calculate the capability, where cables impedance is neglected, and the circuit capacitances and resistances are neglected as well. Moreover, the authors in [5-6] presented a capability estimation of Doubly Fed Induction Generator (DFIG) WTG, while WPP cables and voltage limitation are not included in the capability calculation.

Due to wake effect, WTGs in a WPP are exposed to different wind speeds, hence WTGs active power generation varies within the WPP, which result in non-uniform reserve availability from each WTG. Therefore, controlling these WTGs with the same controller parameters (gain) lead to underutilization of WPP capability. To maximize the reactive power supply from type 3 based WPP, an adaptive control strategy is developed in [7-8] to utilize the WPP reactive power reserve. The adaptive strategy adopted PQ capability curve of WTG to dispatch the reactive power reference point. However, the current capability of WTG only is taken into consideration, and effect of PCC voltage on the WTG capability is not considered. Similarly, an adaptive control scheme based on the thermal capability of type 3 WTG is proposed in [9], where the reactive reserve is calculated based on WTG current capability which again neglect the effect of PCC voltage on the WTG power capability. Therefore, in the backdrop of above, a new adaptive method is proposed to dispatch reactive power generation from WTGs in a WPP. Type 4B IEC 61400-27-1 wind turbine model has been adopted to model the permanent magnet synchronous generator-based WTG.

The major contributions of this paper are: 1) A centralized adaptive WPP control strategy is proposed to enhance the dynamic reactive power compensation performance of WPP, 2) WPP capability surface charts providing high accuracy capability limit, are generated while considering a detailed model of WPP. The rest parts of this paper are organized as follow, the capability of type 4 WTG and WPP is formulated and calculated for the test system in section II. The proposed control strategy is presented in section III. The simulation results are presented in section IV. The paper is concluded in section V.

## II. CAPABILITY OF TYPE 4 WTG

### *A. WTG capability formulation*

The reactive power capability of type 4 WTG, or any full converter interfaced source, is limited by Grid Side Converter (GSC) current and voltage capabilities, respectively. And the overall reactive power capability $Q_{WTG-cap}$ is given by (1).

$$Q_{WTG-c} \quad = \min(Q_i, Q_v) \tag{1}$$

where $Q_i$ and $Q_v$ are WTG reactive power capability decided by current and voltage limitation.

The rated power factor $PF_{rated}$ and maximum permitted DC link voltage $V_{DC\ max}$ of WTG system plays a critical role in determining the reactive power capability of WTG.

The current-limited reactive power capability $Q_i$ depends on thermal limits of the GSC power electronic switches, which is calculated by (2).

$$Q_i = \sqrt{\left(V_{PCC}\, I_{GSC,max}\right)^2 - P^2} \tag{2}$$

Where, P is the active power generation from WTG. $V_{PCC}$is PCC voltage and $I_{GsC,max}$ is the maximum grid side converter current that can be withdrawn from GSC when the withdrawn power is at its rated value and $V_{PCC}$ at its minimum value ($V_{PCC,min}$) [4]. $I_{GSC,max}$ can be calculate from (3).

$$I_{GC,max} = \frac{P_{rated}/PF_{rated}}{V_{PCC,min}} \tag{3}$$

On the other hand, The voltage-limited reactive power capability $Q_v$ is the maximum reactive power that can be injected from a WTG without violating maximum allowed GSC voltage $V_{GSC,max}$. $Q_v$ is mainly affected by $V_{GSC,max}$, active power generation and the impedance between WTG terminals and PCC. $Q_v$ is given in (4).

$$Q_v = \sqrt{\left(\frac{|V_{PCC}|\,|V_{GSC,max}|}{|Z|^2}X\right)^2 - P^2 - \left|V_{PCC,max}\right|^2\left(\frac{X}{|Z|^2}\right)} \tag{4}$$

Where $X$ and $Z$ are the equivalent reactance and impedance between WTG terminals and PCC respectively, and $V_{GSC,max}$ is the maximum GSC voltage which is given by (5) [4],

$$V_{GSC,max} = \frac{f_{max}\, X}{V_{PCC,max}}\sqrt{{P_{rated}}^2 + \left(Q_{rated} + \frac{{V_{PCC,max}}^2}{f_{max}\, X}\right)^2} \tag{5}$$

$f_{max}$ and $V_{PCC,max}$ are the maximum allowed grid frequency and PCC voltage respectively, which are assumed 1.01 pu and 1.05 pu respectively.

The capability of WTGs in a WPP is calculated individually using (1), (2) and (5), and the overall WPP capability is calculated by (6),

$$Q_{WPP-cap} = \frac{S_{WTG\ base}}{S_{WPP\ base}} \times \sum_{i=1}^{n} \mathrm{Q_{WTGi\text{-}cap}} \tag{6}$$

where $S_{WTG\ base}$ and $S_{WPP\ base}$ are the MVA base of WTG and WPP respectively. $Q_{WTGi-cap}$ is the reactive power capability of i$^{th}$ WTG.

### *B. Test system*

The Test system as shown in Fig. 1 has been used to calculate the reactive power capability, and to implement the proposed control strategy. The system consists of six synchronous generators of aggregate capacity of 900 MVA and a 75 MW WPP. The WPP consists of fifteen identical type-4 WTG with a capacity of 5 MW. The cut-in, rated and cut-out wind speeds are 4 m/s, 11 m/s and 25 m/s respectively. WTGs are distant from each other by 9D in both directions, where D is the wind turbine diameter (D= 126 m). The WTGs are modelled as per IEC 61400-27-1 standard [11]. The network has 552 MW load. Rest of the system parameters are given in [10].

In general, wind does not blow always at full speed, and as such WPP does not operate at its rated capacity all the time. Even at WPP rated wind speed, the downstream WTGs in a WPP see less wind speed due to wake effect. Wake effect refers to the decrement in wind speed, hence reduced power generation in downstream WTGs in a WPP. To take the wake effect into account, wake effect model in [12-13] is adopted with WTG aerodynamic specification of NREL 5 MW WTG [14].

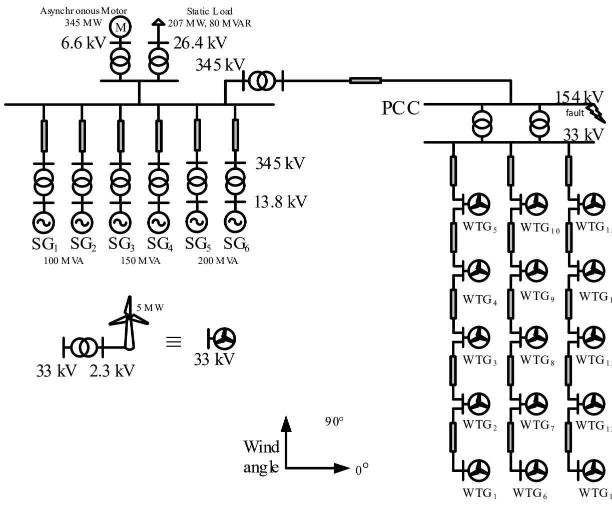


Fig. 1. Test system [10]

### *C. WTGs capabilities*

As it can be observed from (4), voltage-limited reactive power capability is significantly affected by the reactance and impedance between the WTG terminals and PCC. The reactive power capabilities for all WTGs in the test system are shown in Fig. 2 for PCC voltage $V_{PCC} = 1.03\,pu$. The overall WPP capability and individual WTG capability are plotted while considering cable resistance (bolded lines) and without considering it (dashed lines). It is important to observe that voltage-limited reactive power capability dominates the overall capability in this case as the voltage at PCC is close to the maximum allowed magnitude. It can be observed that by neglecting cable resistance, the results are likely to be conservative.

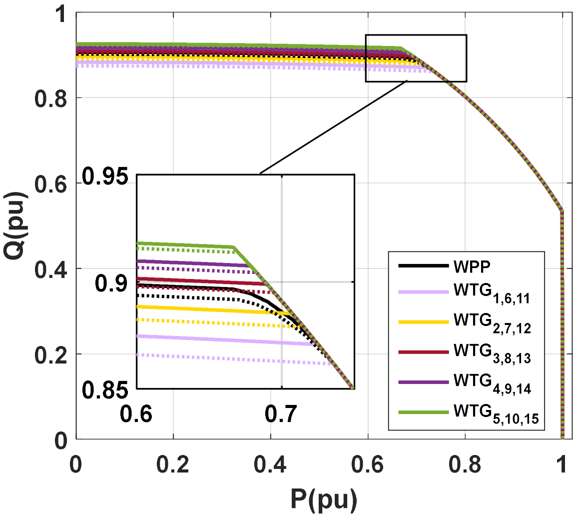


Fig. 2. WTG and WPP capability when Vpcc=1.03 pu.

The dynamic reactive power injection as required by grid code regulation is divided into two modes, first one to ride through the low voltage event when $V_{PCC}$ drop to less than 0.9 pu, known as LVRT grid code requirement. The short term capability of WTG plays the major role in this mode. The second is the voltage regulation requirement, when $V_{PCC}$ is in the range of [0.9, 1.05] pu, where the long term WTG capability decides the maximum steady state reactive power injection/consumption by WTG. As the focus of this paper is on long term reactive power ancillary service, the voltage range where the capability is studied is [0.9- 1.05] pu, while active power generation considered over the entire range [0-1] pu. $V_{PCC,min}$ is assumed to be 0.9 pu in this study.

The dynamic reactive power capability of the studied WPP under generation and consumption mode are plotted in Fig. 3 and 4 respectively. It can be observed from Fig. 3 that WPP capability is maximum (1.13 pu) for minimum active power generation and at 1.017 pu PCC voltage. However, the reactive power injection capability decreases significantly with the increase in PCC voltage. The decrement in reactive power capability is because of the voltage-limited reactive power capability, which may differ from one WPP to another, based on WPP transmission system impedance and maximum allowed WTG terminals voltage. On the other hand, the reactive power consumption capability, as shown in Fig. 4, is maximum (-1.155 pu) for PCC voltage at the maximum limit 1.05 pu and minimum active power generation. The maximum reactive power consumption capability, is restricted by the current limit of GSC. The minimum capability to supply or consume reactive power is observed at WTG rated active power output and minimum allowed PCC voltage.

From WPP point of view, for the same WTG specifications, AC connected offshore WPP has less capability to transmit reactive power from WTG than onshore WPP. The difference between the reactive power transfer capabilities of offshore and onshore WPP is mainly due to long distant WTGs in offshore WPP, and hence high impedance between WTG terminals and the PCC. High impedance between WTG at the offshore site and PCC on the shore side increases the domination of voltage-limited reactive power capability over the current limited one. However, the net reactive power supplied (from both cable capacitance and WTG) might vary depending on the cable length, operating voltage and active power load. The WTG reactive power consumption capability is identical in both the cases, with slight superiority to onshore WPP when net consumed reactive power is compared. Moreover, the reactive power capability of HVDC connected offshore WPP mainly depends on the reactive power capability of the grid side converter of HVDC system.

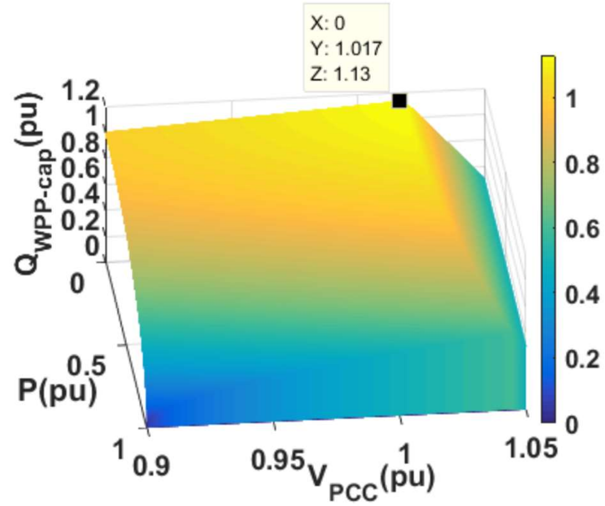


Fig. 3. WPP reactive power supply capability

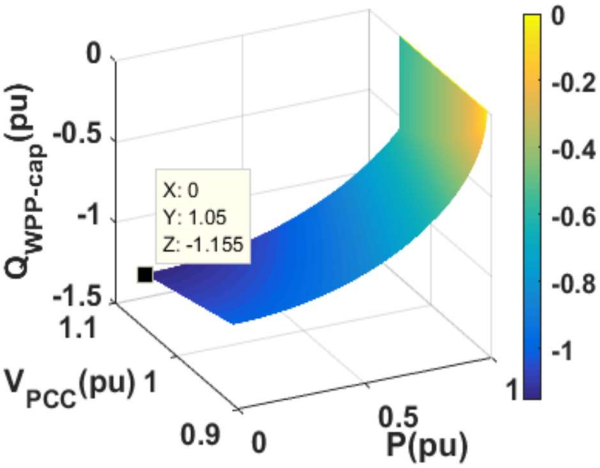


Fig. 4. WPP reactive power consumption capability

## III. Proposed Strategy

Steady state Reactive power support from a WPP can be classified in two types, i) reactive power support mandated by TSO, and ii) reactive power support to the grid beyond this mandatory support. In mandatory compensation, WPP controller is programmed to follow grid code requirement. One of three available types of reactive power support modes is typically imposed by TSO based on PCC voltage level, WPP capacity and the strength of the grid. The first mode, is reactive power mode where WPP is supposed to compensate reactive power as required by the TSO, in the second mode, WPP is supposed to maintain constant power factor. Typically, WPP connected at distribution levels are asked to follow on of these two modes [15]. On the contrary, transmission level connected WPPs follow typically the third reactive compensation mode, known as voltage control mode. WPP in voltage control mode supplies/consumes reactive power in proportion to PCC voltage magnitude. Type 1 and type 2 based WPPs which do not have the active/reactive power decoupling capability are usually fitted with dynamic reactive power compensators to fulfil mandatory reactive power compensation requirement. As this paper is concerned about large scale WPP, the third mode is applied to WPP controller, while reactive power mode is applied to WTGs controllers to follow WPP controller commands.

A reactive power-voltage (Q-V) droop characteristic with a deadband, as shown in Fig. 5, is typically voltage regulation required by TSO. The typical voltage deadband value is generally $\pm 0.01$ pu from the scheduled voltage set point ($V_{com}$), while a typical Q-V droop in a WPP is generally set in the range of 2%- 10%. Q-V droop of less than 2% may result in grid voltage fluctuations, and thus such lower droop values are generally avoided. However, in case of a weak grid, such small Q-V droop values may be employed for more effective voltage control [15]. $\Delta V_{pcc}$ in Fig. 5 refers to PCC voltage deviation from the commanded voltage by TSO $\Delta V_{pcc} = V_{PCC} - V_{com}$.

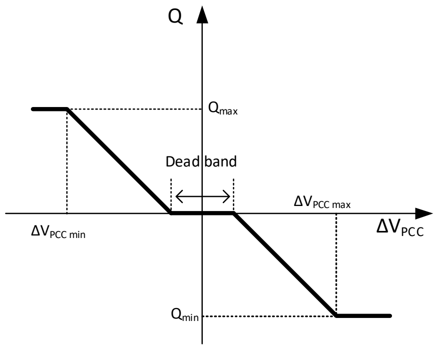


Fig. 5. Typical Q-V droop characteristic.

The conventional voltage control strategy which is typically employed to comply with mandatory grid code requirement is shown in Fig. 6. A look-up table of the desired Q-V droop characteristic or deadband with droop controller is employed to generate the WPP reactive power reference ( $Q_{WPP\,ref}$ ) from $\Delta V_{pcc}$ signal. The reactive power compensated at PCC ($Q_{WPP}$) is measured and compared with $Q_{WPP\,ref}$. WTGs reactive power references are generated as shown in Fig. 6 and communicated to WTGs. An 8% reactive power-voltage droop with 1% deadband characteristic has been adopted for conventional strategy in this study. The proposed reactive power control strategy is based on the reactive power capability of WPP to supply/consume reactive power with the mandatory grid code requirement as the minimum limit and the maximum capability of WPP as the maximum limit. The reactive power reference is dispatched among the WTGs of WPP, based on their individual capabilities with respect to WPP capability. The individual WTG and WPP capability calculated in Section II are employed in the proposed strategy.

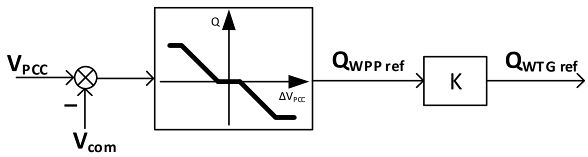


Fig. 6. Conventional reactive power reference point calculation.

Fig. 7 shows the schematic of the proposed WPP reactive power controller. The difference between the measured PCC voltage and the commanded one is calculated (in pu) and passed through deadband of 0.01. The voltage error is multiplied by the instantaneous reactive power reserve and scaled up by gain K to generate the WPP reactive power reference. The reactive power reference signal is limited by a limiter with minimum value of mandatory grid code requirement and the capability surface based maximum reactive power capability of WPP being the upper limit. The WPP reactive power reference is dispatched and communicated to WTGs controllers after being scaled adaptively based on their respective capability. This is done by employing adaptive participation factors ($K_1$, $K_2$, …, $K_n$), where n is the number of WTGs in WPP. Fig. 8 shows how adaptive participation factors are calculated. WTGs individual capability surfaces are calculated as described in Section II, the instantaneous capability of $WTG_i$ is calculated and divided by the instantaneous WPP capability to update the participation factor $K_i$.

## IV. Simulation Results

The effectiveness of the proposed strategy has been tested on the test system shown in Fig. 1, and developed DIgSILENT PowerFactory platform. Wind speed is assumed to be rated (11 m/s) while wind angle is considered as 45°, and the wake effect has been calculated accordingly. The reactive power capability surfaces of WTGs and WPP are calculated and being fed to controllers. The voltage drop event is simulated by a three phase fault through a fault impedance $Z_f$ at WPP PCC bus. The severity of the voltage drop is controlled by changing the impedance magnitude. Two case studies as described below have been considered.

### *A. Case 1*

In this case, created fault of 1 sec duration is introduced at $t = 1\ sec$. Though the wind speed is the rated wind speed, pre-fault WPP active power generation (0.868 pu) is less than the WPP rated power due to the wake effect, where only WTGs (1,2,3,4,5,6 and11) are exposed to rated wind speed, the rest WTGs wind speed are calculated as per the adopted wake effect model. Fig. 9 shows measured active power,

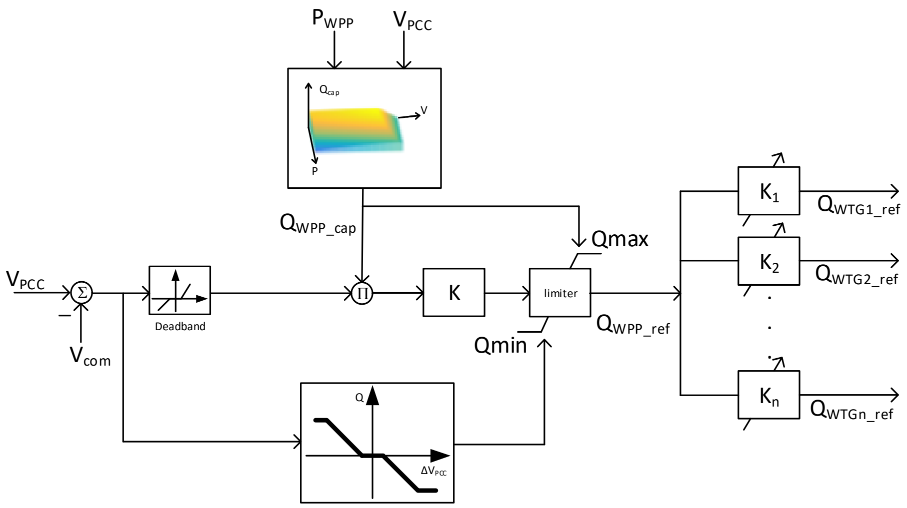


Fig. 7. Proposed centralized adaptive WPP reactive power controller.

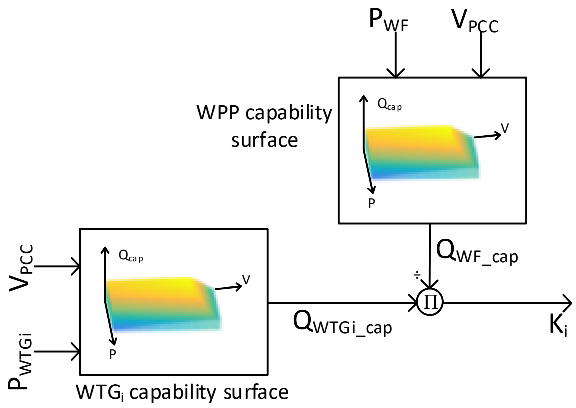


Fig. 8. Reactive power dispatch

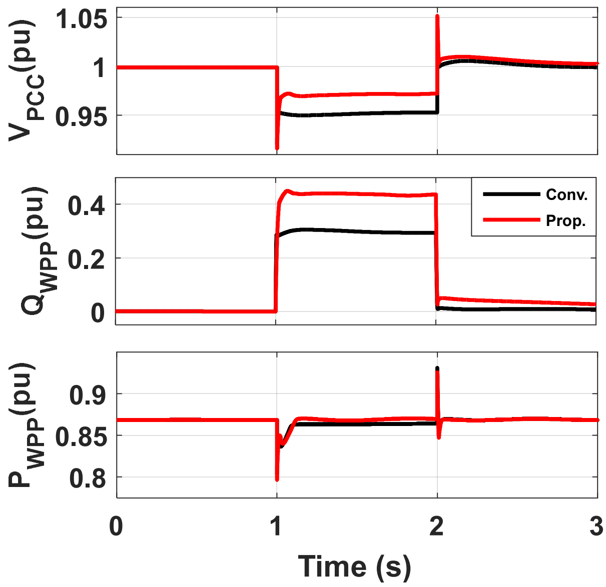


Fig. 9. Case 1: WPP conventional and proposed results

reactive power and voltage magnitude at PCC for both the proposed and conventional strategy. It can be observed that the performance of the proposed strategy is superior to the conventional one. The reactive power supplied by WPP is increased by 0.14 pu when proposed strategy is implemented, which is reflected in PCC voltage improvement from 0.95 pu to 0.97 pu. The active power pumped during the voltage drop event is also improved and is closely following the pre-fault value, which is due to improved voltage.

Fig. 10 shows individual WTG reactive power and terminal voltage response. While in conventional strategy, a uniform reactive power reference is generated, the proposed strategy dispatches the required reactive power among the WTGs based on their reactive power reserve. Therefore, WTGs (1,2,3,4,5,6,11) supply reactive power less than the rest of the WTGs as they see rated wind speed and generate rated active power. It can also be observed that in the proposed strategy, WTG terminal voltages are higher, which is due to additional reactive power injection.

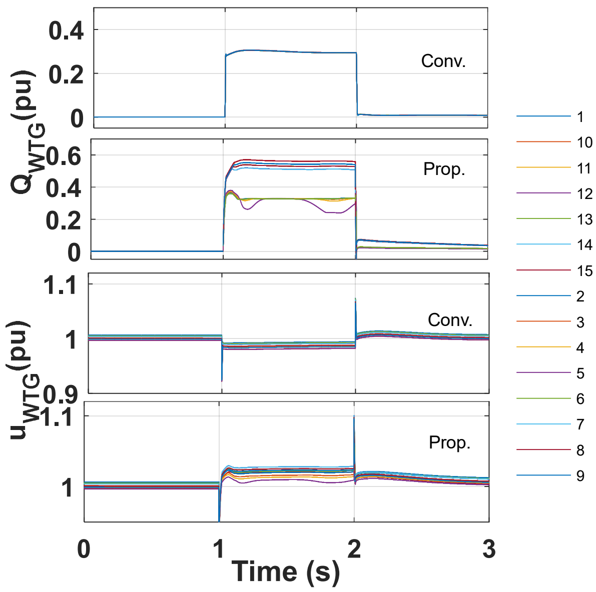


Fig. 10. Case1: WTGs conventional and proposed results. (number on legend represents the WTG number)

### B. Case 2

In this case, a less severe voltage dip is introduced. The wind speed and direction are assumed to be the same as that in Case 1. Fig. 11 and 12 show WPP and WTG responses respectively. The additional reactive power injected in the proposed strategy is 0.12 pu, compared to conventional grid code requirement. The PCC voltage is improved to 0.98 pu in the proposed strategy, as compared to 0.96 pu in conventional control strategy. WTG terminal voltages are in the allowed range in both the strategies.

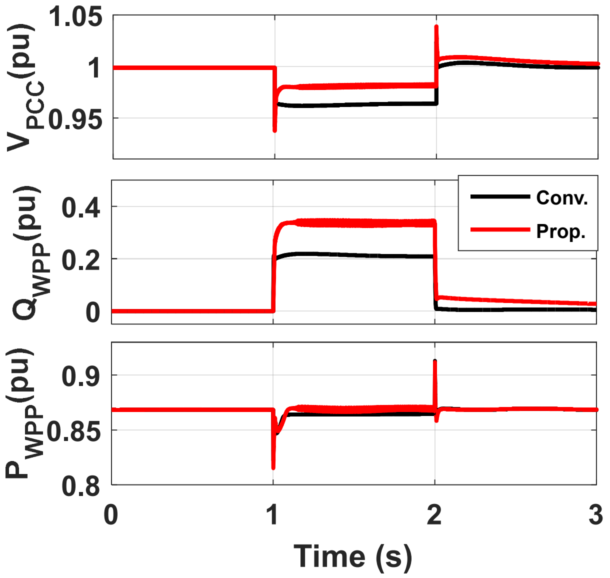


Fig. 11. Case 2: WPP conventional and proposed results

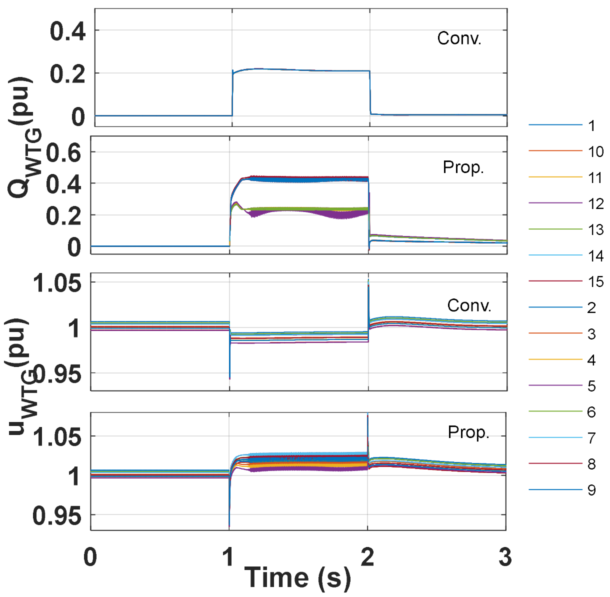


Fig. 12. Case2: WTGs conventional and proposed results (number on legend represents the WTG number)

## V. Conclusion

In this paper, the capability of type 4 WPP to provide dynamic reactive power compensation for steady state voltage control is studied. A detailed WPP model and factors like cable resistance, wake effect and voltage limited reactive power capability are taken into consideration to get a precise reactive power capability surface for individual WTG and the overall WPP. An adaptive WPP voltage control strategy based on these capability surfaces is proposed to empower the WPP to participate in voltage control ancillary service. The reactive power distributed among WTGs adaptively based on their reactive power reserves. The reactive power required by grid code regulation is taken as minimum required reactive power supply/consumption, while the rest of the capability margin is used to control the PCC voltage. The proposed strategy has shown a better dynamic reactive power compensation and effective voltage control. The proposed strategy is currently under further development by the authors.

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