# Impact of different load types on voltage stability of power system considering wind power support

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***Abstract*—This paper analyses impact of different load types on voltage stability of a power system with wind power. To analyse voltage stability, dynamic as well as static static voltage stability assessment are performed. Dynamic model of wind turbine based on Type 4A IEC 61400-27-1 is used to develop an aggregated wind power plant model including the wind power collection system. Polynomial load model is used to represent different load types, namely, constant impedance, constant current and constant power loads. With respect to voltage stability assessment, eigenvalue analysis is used for static voltage stability assessment to determine stability of a particular operating point. Voltage collapse proximity indicator is used as dynamic voltage stability assessment tool to analyse the proximity of an operating point from voltage collapse. Impact of load type on voltage stability is discussed. Impact of reactive power support from wind power plant for the different load types is analysed and discussed. From the case studies performed, it is observed that effect of reactive power support from WPP varies depending on the load type. Results show that distance to instability for the same reactive power support from WPPs can be greater in case of voltage dependent loads than that of constant power loads.**

## I. INTRODUCTION

Voltage stability is defined as “the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition” [1]. The driving force for voltage instability are loads. In an attempt to restore power consumption of load, load dynamics often push the system beyond total transmission and generation capability of the system. This causes voltage instability of the system [2].

It is difficult to identify load characteristics at a given operating point. This makes the process of load modelling difficult. Most commonly used load type is constant power load, where active and reactive power consumption of the load remains constant regardless of change in system voltage. However, system loads are combination of different load components with different voltage sensitivities. Two widely used load characteristic models are (i) exponential load and (ii) polynomial load. Both load models can be constant impedance (Z) load, constant current (I) load, constant power (P) load or a combination of of them, i.e. constant impedance, constant current and constant power (ZIP) load. Constant power load is unaffected by voltage changes, while all other load types are voltage dependent. Since actual power consumed is dependent on load characteristic, maximum power transfer limit is affected by load characteristic model. Due to composite nature of load, ZIP load model is often used in power system stability analysis. Load modelling and its impact on voltage stability indices have been studied in [3].

In future power systems with large share of converter-connected renewable energy sources, reactive power sources (traditionally, synchronous generators) will be reduced [4]. To maintain voltage stability in future converter-connected power systems, either additional reactive power compensation devices need to be installed or reactive power capability of converter connected generations, like wind power plant (WPP), could be utilised. Especially in cases where WPPs are connected close to load centres, utilisation of existing reactive power capability can save additional expense on installation of large compensation devices. In case, reactive power available from WPP is not sufficient, a smaller compensating device could be installed.

To assess voltage stability of a system both static and dynamic analysis can be used. Dynamic analysis involving time-domain simulations can capture dynamic characteristics of loads as well as other components of the system such as, on load tap changing transformers. Static analysis can be used to determine maximum power transfer capability of the system as well as to identify the distance to instability or voltage collapse for any particular operating point.

In this paper, the impact of different load types on voltage stability of system is described and analysed. It is shown how constant power loads having most strict power consumption can trigger voltage instability earlier, while voltage dependent loads, which can adjust their consumption as per system voltage, help in mitigating voltage instability. These characteristics of loads are studied on a system with WPP which does not provide reactive power support. Furthermore, it is also studied how the same amount of reactive power support can lead to different operating points (with respect to proximity to voltage collapse) depending on the load type.

## II. MODELLING

### A. Wind Turbine Model

The wind turbine (WT) model in this paper is based on Type 4A WT model defined as in IEC standard 61400-27-1 [5], [6]. Details of the WT model are described in [7]–[9]. Simplified block diagram of the reactive power control block is shown in Fig. 1. The reactive power control block is able to operate in voltage control, reactive power control, power factor control and open/closed loop control modes. As shown in Fig. 1, the reference signal to the reactive power control block can be voltage, reactive power or power factor setpoint. Based on the chosen control mode, reference and

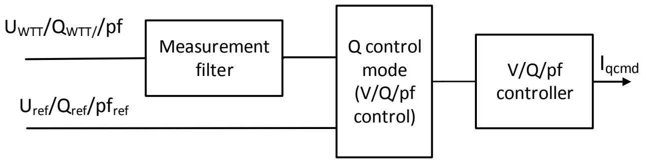

Fig. 1: Simplified schematic diagram of reactive power control block

measured signals are chosen. Error between measured and reference signal are then passed through an anti-windup PI controller to generate reference reactive current signal.

### B. WPP model

In this paper aggregated WPP is modelled based on work done by authors in [10]. Aggregated WPP model consists of aggregated WT generator together with equivalent impedance of aggregated collector system as shown in Fig. 2. The WPP model also includes an on load tap changing (OLTC) WPP transformer. The OLTC cannot be seen in Fig. 2, because aggregation of WPP is done up to the low voltage side of the OLTC WPP transformer. This OLTC transformer helps to maintain the WPP collector system voltage at desired voltage level, generally, 1 pu. WPP model together with OLTC transformer can be seen in Fig. 3.

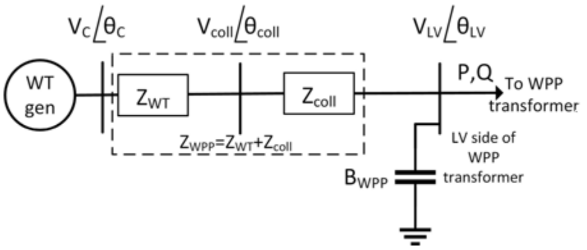

Fig. 2: Aggregated WPP model [10]

### C. Load model

According the definition given in [2], voltage instability is load driven. Hence it is important to have proper load models in order to perform a voltage stability analysis. Different load types have different load power consumption with respect to system voltage. As different load types exhibit different voltage characteristics, one way to represent load is in form of polynomial expression give by equations 1 and 2.

$$P = P_0\left[a_P\left(\frac{V}{V_0}\right)^2 + b_P\left(\frac{V}{V_0}\right) + c_P\right] \tag{1}$$

$$Q = Q_0\left[a_Q\left(\frac{V}{V_0}\right)^2 + b_Q\left(\frac{V}{V_0}\right) + c_Q\right] \tag{2}$$

where,
P = load active power consumed,
Q = load reactive power consumed
$V_0$ = reference voltage
$P_0$ = load active power consumed at reference voltage
$Q_0$ = load reactive power consumed at reference voltage
$a_P, b_P, c_P$ = coefficients defining proportion of constant impedance, constant current and constant power loads respectively in active load component
$a_Q, b_Q, c_Q$ = coefficients defining proportion of constant impedance, constant current and constant power loads respectively in reactive load component

and $a_P + b_P + c_P = a_Q + b_Q + c_Q = 1$.

## III. VOLTAGE STABILITY ASSESSMENT

In this paper, a set of study cases has been carried out to investigate the impact of load types on voltage stability of system with reactive power support from WPP. This has been done in three steps: (1) perform dynamic voltage stability assessment to identify critical operating point as well as determine characteristic of an operating point (2) perform eigenvalue analysis to identify whether a system operating point is stable or not (3) analyse line Voltage Collapse Proximity Indicator (VCPI) to quantify distance to voltage collapse.

### A. Eigenvalue Analysis

Eigenvalue analysis of Jacobian matrix determines response of the system close to an equilibrium. Based on voltage stability evaluation in [11], the Jacobian matrix can be decomposed into:

$$J = \xi \Lambda \eta \tag{3}$$

where,
$\xi$ = right eigenvector matrix of Jacobian
$\eta$ = left eigenvector matrix of Jacobian
$\Lambda$ = diagonal eigenvalue matrix of Jacobian

Each eigenvalue and the corresponding right and left eigenvectors represent one mode of the system. Magnitude of each eigenvalue, determines the weakness of the corresponding modal voltage. Smaller magnitude of the eigenvalues depicts a weaker mode. When the eigenvalue of a particular mode reaches 0, the mode becomes unstable. Hence the minimum eigenvalue of a system indicates whether the system is stable or not.

### B. Voltage Collapse Proximity Indicator

VCPI was defined by Moghavvemi and Faruque in [12]. In this method, each line of the system is investigated by calculating VCPI as given by equation 4.

$$VCPI = \frac{P_r}{P_{rmax}} \tag{4}$$

where,
$P_r$ = Real power transferred to the receiving end
$P_rmax$ = Maximum real power that can be transferred

Maximum real power that can be transferred can be calculated from equation 5.

$$P_{rmax} = \frac{V_s^2}{Z_s}\frac{cos\phi}{4cos^2\frac{\theta-\phi}{2}} \tag{5}$$

where,
$V_s$ = sending end voltage
$Z_s\angle\theta$ = line impedance
$Z_r\angle\phi$ = load impedance

Since VCPI is the ratio between the real power transferred and the maximum real power that can be transferred, VCPI varies from 0 at no load condition to 1 at maximum permissible loading condition.

## IV. CASE STUDY

The test system studied in this paper is a 3 bus power system model with aggregated WPP of size 108 MW. The single line diagram of the network is shown in Fig. 3. A set of study cases has been performed and investigated. Simulations have been done in DIgSILENT PowerFactory.

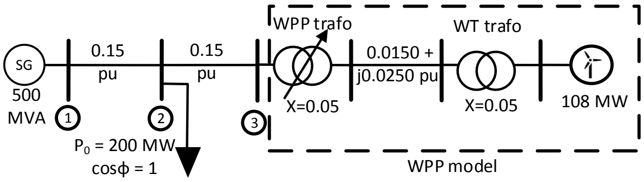

Fig. 3: Test system (all parameters in pu on 100 MVA base)

### A. Case : No reactive power support from WPP

In this case study, impact of load type on power system stability is investigated. Q reference of the reactive power control block of the WT generator is set to 0. During simulation, the load is increased from 200 MW to 400 MW in one hour duration. Voltage profile at the load bus (bus 2 in Fig. 3) is plotted in Fig. 4 for constant power, constant current and constant impedance load types. It can be observed from Fig. 4 that load voltage drop is maximum in case of constant power load. Due to voltage sensitivity of constant current and constant impedance load types, load power is moderated at lower voltages causing less voltage drop at the load bus.

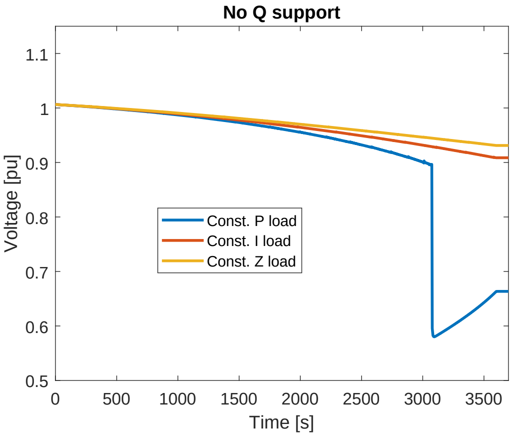

Fig. 4: Load bus voltage for three different load types with no reactive power support from WPP

Further, the impact on power system stability is analysed using eigenvalue analysis. Minimum eigenvalue of the 3-bus test system is shown in Fig. 5. It can be observed that minimum eigenvalue reaches 0 in case of constant power load type at 3235s of simulation time. This implies that the system is unstable beyond this point in simulation. It is noticed that minimum eigenvalue in case of other two load types remains positive throughout simulation, which implies that the system stable for the other two load types. From Fig. 5 it is observed that the system becomes unstable for constant power load type, but remains stable for constant current and constant impedance load types. However, distance to instability cannot be analysed from eigenvalues. For this purpose VCPI index of line 1-2 is studied and results are plotted in Fig. 6. Notice that VCPI index reaches 1 for constant power load, while for constant current and constant impedance loads VCPI index is 0.78 and 0.72 respectively. It is remarked that the distance to instability for constant impedance load is greater than that for constant current load. It is to be remembered that VCPI closer to unity implies system is prone to instability.

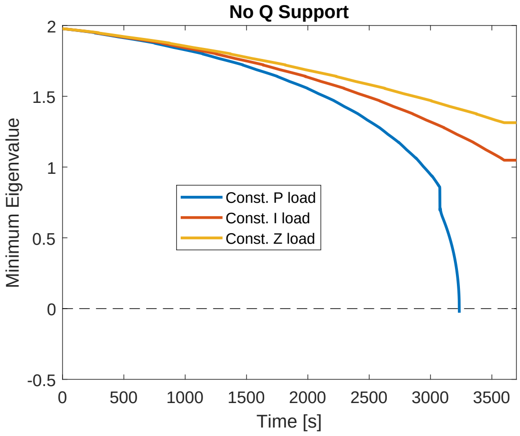

Fig. 5: Minimum eigenvalue of system for three different load types with no reactive power support from WPP

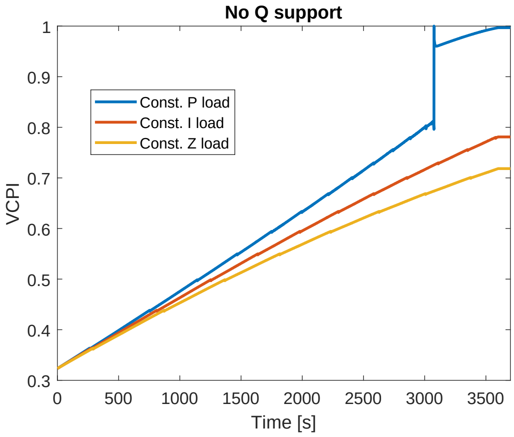

Fig. 6: Voltage collapse proximity indicator for three different load types with no reactive power support from WPP

All the above results illustrates that in the case when WPP does not contribute with reactive power, voltage dependent loads enhance voltage stability of system by lowering their load power demand at lower voltages, while constant power loads stress the system whenever the system voltages are low.

### *B. Case : 10% reactive power support from WPP*

In this case, the previous study is repeated with Q reference of the reactive power control block of WT generator set to 0.1 pu. Voltage profile of the load bus for the three different load types are plotted in Fig. 7. It can be observed that voltage profile improved compared to no Q support case. Analysis of minimum eigenvalues of the system, illustrated in Fig. 8, indicates that the instability is again caused by the constant power load. However, the instability occurs at a later point than in case of 0 reactive power support. It should be noticed that the minimum load bus voltage is improved with increase in reactive power support from WPP. However, a similar analysis of VCPI indices shows that the distance to instability is similar to the no reactive power support case. Comparison of minimum load bus voltage and VCPI are given in Table I and Table II respectively. It can be therefore concluded that although minimum load bus voltage is improved with 10% reactive power support from WPP, the distance to voltage instability is unaffected.

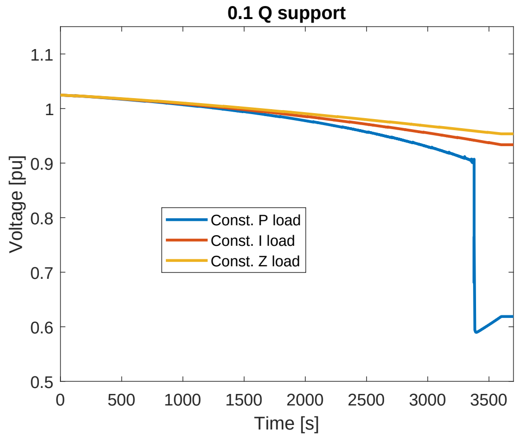

Fig. 7: Load bus voltage for three different load types with 0.1 p.u. reactive power support from WPP

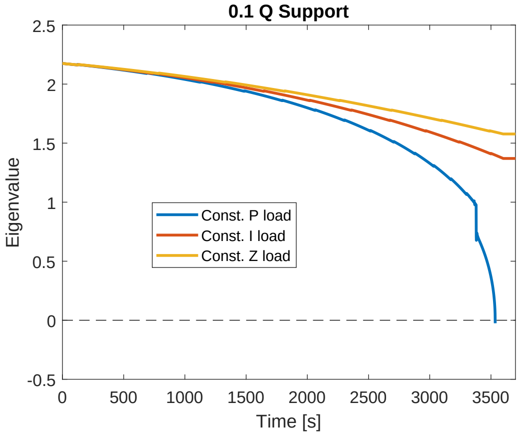

Fig. 8: Minimum eigenvalue of system for three different load types with 0.1 p.u. reactive power support from WPP

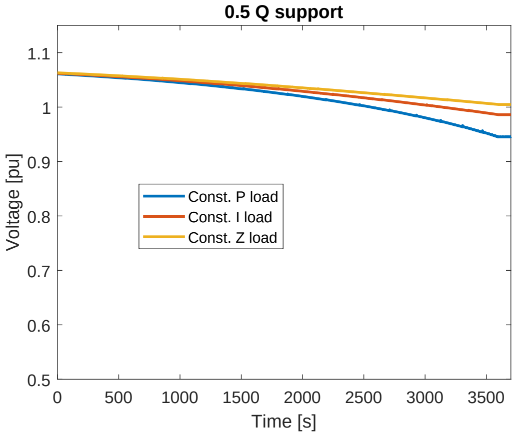

Fig. 9: Load bus voltage for three different load types with 0.5 p.u. reactive power support from WPP

### *C. Case : 50% reactive power support from WPP*

In this study Q reference is set to 0.5 pu. Load bus voltage profile are shown in Fig. 9. It can be observed that injection of considerable amount of reactive power in the system causes load bus voltage to rise above 1 pu at lower values of load power demand. However, voltages remain within acceptable limit of 1.05 pu. When load power demand is doubled (towards the end of simulation time), voltages remain close to 1 pu for voltage dependent loads, as shown in Table I. In this case, the system remains stable for constant power load. The analysis of the minimum eigenvalues of the system indicates an improvement of the system stability, as they remain positive for all load types as shown in Fig. 10. This can also be observed from Table II, as that distance to voltage instability is improved for all load types. This study case indicates thus the benefical impact of reactive power support from WPPs on voltage stability for different types of loads.

TABLE I: Minimum voltage at load bus (in pu) for different load types with varying degree of reactive power support from WPP

| WPP Q support [pu] | Constant P load | Constant I load | Constant Z load |
|---|---:|---:|---:|
| 0 | unstable | 0.91 | 0.93 |
| 0.1 | unstable | 0.93 | 0.95 |
| 0.5 | 0.95 | 0.99 | 1 |

TABLE II: Voltage Collapse Proximity Indicator for different load types with varying degree of reactive power support from WPP

| WPP Q support [pu] | Constant P load | Constant I load | Constant Z load |
|---|---:|---:|---:|
| 0 | 1 | 0.78 | 0.72 |
| 0.1 | 0.98 | 0.75 | 0.69 |
| 0.5 | 0.79 | 0.67 | 0.59 |

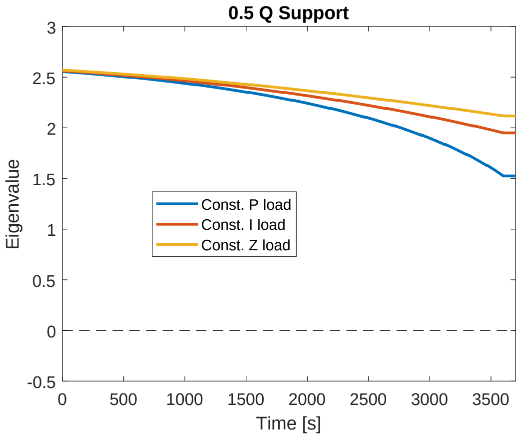

Fig. 10: Minimum eigenvalue of system for three different load types with 0.5 p.u. reactive power support from WPP

## V. CONCLUSION

In this paper, impact of different load type on system stability is studied. It is concluded that voltage dependent loads helps maintaining system stable by reducing their load power demand proportional to the system voltage. Constant power loads are rigid in their load power demand and hence can affect system stability adversely during stressed system conditions. Reactive power support from WPPs helps to maintain system voltages in desired range of operation. However, the effect of reactive power support from WPP varies depending on the load type. Furthermore, the results have shown that distance to instability for the same reactive power support from WPPs can be greater in case of voltage dependent loads than that of constant power loads.

## VI. FUTURE WORK

Future work will be directed toward analysing the situation that loads require different reactive power. In case reactive power capability of WPP is not sufficient to provide the required reactive power, additional reactive power compensation devices needs to be installed. This analysis provides the stepping stone for dimensioning of compensating devices in addition to reactive power support from WPP.

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## REFERENCES

[1] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor *et al.*, "Definition and classification of power system stability," *IEEE transactions on Power Systems*, vol. 19, no. 2, pp. 1387–1401, 2004.

[2] T. Van Cutsem and C. Vournas, *Voltage stability of electric power systems*. Springer Science & Business Media, 2007.

[3] S. Chakrabarti, "Static load modelling and voltage stability indices." *International Journal of Power & Energy Systems*, vol. 29, no. 3, 2009.

[4] A. Ellis, R. Nelson, E. Von Engeln, R. Walling, J. McDowell, L. Casey, E. Seymour, W. Peter, C. Barker, and B. Kirby, "Reactive power interconnection requirements for pv and wind plants–recommendations to nerc," Technical Report, 2012.

[5] *IEC 61400-27-1: Electrical simulation models – Wind Turbines*, Std., February, 2015.

[6] K. Das, A. D. Hansen, and P. E. Sørensen, "Understanding iec standard wind turbine models using simpowersystems," *Wind Engineering*, vol. 40, no. 3, pp. 212–227, 2016.

[7] L. Petersen, M. Altin, K. Shahid, R. L. Olsen, F. Iov, A. D. Hansen, and X. Han, "Specifications for regen plant model and control architecture," 2018.

[8] A. D. Hansen, M. Altin, I. D. Margaris, F. Iov, and G. C. Tarnowski, "Analysis of the short-term overproduction capability of variable speed wind turbines," *Renewable Energy*, vol. 68, pp. 326–336, 2014.

[9] M. Sarkar, M. Altin, A. D. Hansen, and P. E. Sørensen, "Impact of wind power plants on voltage control of power system," in *1st International Conference on Large-Scale Grid Integration of Renewable Energy in India*, 2017.

[10] M. Sarkar, M. Altin, P. E. Sørensen, and A. D. Hansen, "Reactive power capability model of wind power plant using aggregated wind power collection system," *Energies*, vol. 12, no. 9, p. 1607, 2019.

[11] B. Gao, G. Morison, and P. Kundur, "Voltage stability evaluation using modal analysis," *IEEE transactions on power systems*, vol. 7, no. 4, pp. 1529–1542, 1992.

[12] M. Moghavvemi and O. Faruque, "Real-time contingency evaluation and ranking technique," *IEE Proceedings-Generation, Transmission and Distribution*, vol. 145, no. 5, pp. 517–524, 1998.