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Voltage Stability Analysis and Improvement of Power System With Increased SCIG-based Wind System Integration

Bukola Babatunde Adetokun
Department of Electrical Engineering, Pan African University Institute for Basic Sciences, Technology and Innovation, Jomo Kenyatta University of Agriculture and Technology,
Nairobi, Kenya.
jesutunde@gmail.com

Christopher Maina Muriithi
Electrical Engineering Department, Murang'a University of Technology, Murang'a, Kenya.
cmmuriithi@mut.ac.ke

Joseph Olorunfemi Ojo
Department of Electrical and Computer Engineering, Tennessee Technological University, Cookeville, Tennessee, USA.
Jojo@tntech.edu

***Abstract*—This paper presents voltage stability analysis and improvement of power system when there is increase in wind power penetration. Loading parameter-Voltage curve was used to calculate the loadability and the megawatt margin as the penetration level (PL) of Squirrel Cage Induction Generator Wind System (SCIG-WS) increases. Furthermore, the effects of increasing SCIG-WS PL on grid losses and equipment loading have been investigated. The results show that for the IEEE 14-bus system utilised as case study, the maximum SCIG-WS PL obtainable without reactive power compensation is 49.45%. However, increasing PL has considerable overloading effects on critical transmission lines and generators, which therefore limits the permissible PL to 33.73%. The results also indicate that the application of Static Var System (SVS) yields a significant enhancement in system loadability and reduction in power losses of the system.**

***Index Terms*— Voltage stability; SCIG-based wind energy conversion systems; Grid integration; Loadability limits; Reactive power compensation.**

I. Introduction

Renewable energy (RE) conversion and integration has attracted much attention in recent years and is now a main area of interest in the energy sector. This is informed by the need to address climate change effects because of the perennial exploitation of fossil-fuel for power production and the need to supply the rising demand in energy worldwide [1, 2]. Thus, renewable and sustainable energy alternatives to the traditional fossil fuel-based power generation are being developed and deployed in different parts of the world. Billions of dollars are committed annually to renewable energy research and development in North America, Europe, Japan, China, Australia, India and Brazil [3]. Renewable energy options are also being considered and explored in Africa and Middle-East. For instance, a significant percentage of the total generation in Kenya are from renewable sources. All these indicate that renewable energy generation and grid integration has gained significant global and local interests [4, 5]. Among the world's renewable sources, wind is mostly utilised and more than 591GW of Wind Energy Conversion Systems (WECS) have been installed by the end of 2018 [6].

Several authors have discussed and analysed the possibilities and issues regarding 100% renewable energy grid [7-9]. A considerable burden of proof has been provided in [7], arguing that 100% RE PL is impracticable because the attendant distribution and transmission expansion together with the required support services are too enormous for such grid. In addition, evidence from literature has shown that one of the main items to consider when increasing renewable energy integration is contemplated is voltage stability [10]. However, the authors in [8] indicate that 100% RE grid is both economically viable and technically feasible, citing that some nations have already attained 100% or near 100% RE grid [9].

This study focuses on the voltage stability analysis and improvement of power system with increased SCIG-WS. Voltage stability is an important consideration for increasing renewable energy penetration level and different works have been carried out to study the effects of high share of renewable energy on voltage stability of power system [11-21]. In [11], a probabilistic method to voltage stability analysis of renewable system integrated to the grid has been studied using loading parameter-voltage and reactive power-voltage curves. The work pointed out the demerits associated with the intermittency of renewable generation. The emergency control and stability mechanism of wind-integrated power grid has been analysed in [13]. It was shown that the major issue is voltage stability when there is increase in wind power penetration. Therefore, a control scheme to mitigate voltage instability due to increased wind integration was proposed. In [17], a methodology for equipment upgrade planning and reactive power compensation for voltage stability improvement of grid-tied WECS was presented. The study in

[19] shows that the combined operation of wind and natural gas systems can reduce the cost of operation and provide system flexibility while improving voltage stability. Moreover, the voltage stability analysis of power system under increased DFIG-based WECS integration has been carried out in [21].

None of the studies above examined the determination of the maximum and permissible SCIG-WS penetration limit considering voltage stability and loading effects of WECS on essential system elements. Therefore, this study investigates the influence of increased SCIG-WS penetration level on power system voltage stability and the resulting effects on critical system element loadings in order to establish the maximum allowable SCIG-WS penetration level. In addition, voltage stability improvement technique for increasing the SCIG-WS integration with Static Var System (SVS) has been studied. SCIG-WS has been considered in this work because it is a relatively cheaper alternative compared to other advanced WECS configurations.

In this work, the SCIG-WS penetration level (PL) is the fraction of the real power produced by the SCIG-WS to the combined real power produced by all generators in the system. This definition was also adopted in [22].

The outline of the remaining parts is as follows: Section 2 presents a brief overview of PV curve analysis. Section 3 details the results and discussion on the voltage stability analysis of the study system with increased SCIG-WS PL and Section 4 presents the results of voltage stability enhancement using SVS. Conclusion of this work is provided in Section 5.

II. Loading parameter-voltage curve Analysis

Loading parameter-voltage (λ-V) curve is often used to study static voltage stability in power systems. The turning point of this curve determines the point of maximum loading of the system and the voltage at which it occurs. This voltage is called the critical voltage. The λ-V curve can be obtained from continuation power flow (CPF). Details of CPF can be found in [23].

The λ-V curve analysis is employed in this study to evaluate the influence of increased SCIG-WS integration on power system's voltage stability. The resulting effects of higher SCIG-WS integration on grid losses and loadings of system element are also examined. The major elements considered are the transformers, transmission lines and generators. The Maximum Loading Parameter, λ_{max} and the megawatt margin (MWM) derived from λ-V curve analysis and utilised in this work to study voltage stability of the system can be expressed as:

$$\lambda_{max} = \left(\frac{P_{max}}{P_{base}}\right) - 1 \tag{1}$$

$$MWM = P_{max} - P_{base}$$

where P_{max} is the maximum obtainable load and P_{base} is the nominal basecase load

The study system used in this work is the IEEE 14-bus system and it has a total basecase load of 259MW (2.59pu). The one-line diagram of the IEEE 14-bus test system is shown in Fig. 1 and the system parameters of the DIgSILENT PowerFactory model are provided in [24]

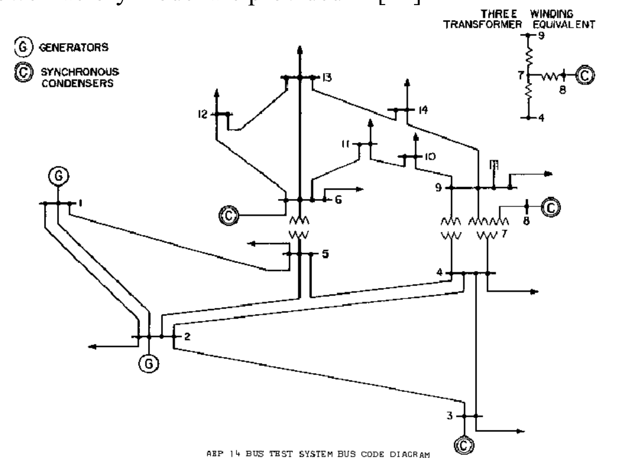

Fig. 1. IEEE 14-bus one-line diagram

III. Voltage Stability Analysis for increased SCIG-WS Penetration

The results of the voltage stability analysis with increasing SCIG-WS penetration level are presented and discussed in this section.

A. Influence of Increased SCIG-WS Integration on Maximum Loading Indices

The influence of integrating SCIG-WS on the maximum loading indices are investigated here. Figures 2a and 2b show the characteristic behaviour of λ_{max} and MWM with SCIG-WS penetration. It can be observed that the system loadability decreases considerably as the SCIG-WS penetration increases. The figures show that the highest PL obtainable for SCIG-WS is about 49.45% (149.625MW). This is because the SCIG-WS is incapable of generating reactive power but absorbs reactive VAR from the power system. Thus, the more the penetration level, the higher the reactive power absorbed from the grid by the SCIG-WS, thereby resulting to a shortage of reactive power within the system and consequently to voltage instability of the grid. This is illustrated in Fig. 3, which shows the reactive power absorbed by the SCIG-WS as the penetration level increases both at normal base case loading and at maximum loading point.

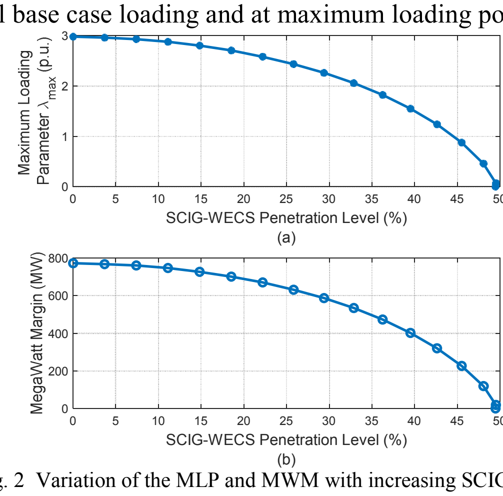

Fig. 2 Variation of the MLP and MWM with increasing SCIG-WS Penetration Level

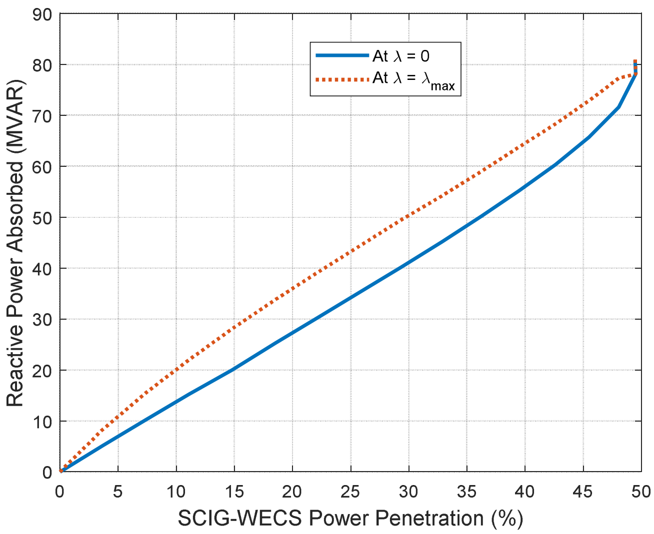

Fig. 3 SCIG-WS Reactive Power with Increase in Penetration Level

The grid losses in terms of the real and reactive power losses are depicted in Fig. 4(a) and Fig 4(b) respectively. The figures indicate that with increased SCIG-WS integration, the grid losses initially reduces, and then later begins to increase at higher penetration levels. The active power loss returns to its base case value of 13.54MW at about 29.4% penetration level, after which it continues to rise with increasing penetration level as shown in the figure. Also, the reactive power loss returns to its base case value of 27.24MVAR at about 36.3% penetration level and then continues to rise significantly at higher penetration level.

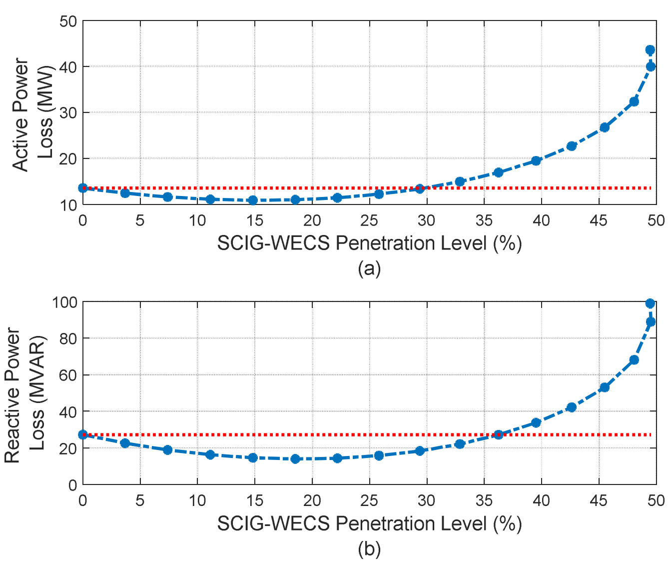

Fig. 4 Variation of the Active and Reactive Power Losses with Increasing SCIG-WS Penetration Level

B. *Influence of Increased SCIG-WS Integration System Element Loading*

The influence of increased SCIG-WS on grid system element loading is examined here. Since it is important that grid system elements are not overloaded, this subsection gives insights on the loading influence of increased SCIG-WS integration. When loading of an equipment goes beyond 80%, such equipment needs to be watched closely to avoid overloading.

1) Generators: The influence of increased SCIG-WS integration on generator loading is illustrated in Fig. 5. It can be observed from the figure that only bus 6 generator loading increased beyond 100% to reach a value of 128.43% at the maximum SCIG-WS power penetration value of 49.45% (149.625MW). At this maximum penetration level, the bus 6 synchronous compensator, with a nominal rating of 100MVA, generates a reactive power of 128.43MVAR. Also, bus 6 generator reaches 80% loading at 42.61% SCIG-WS PL, while it attains 100% loading at 47.4% PL. However, the percentage loading for the remaining generators are less than 61% at all PLs. This implies that only generator 6 loading is significantly affected by increased SCIG-WS integration.

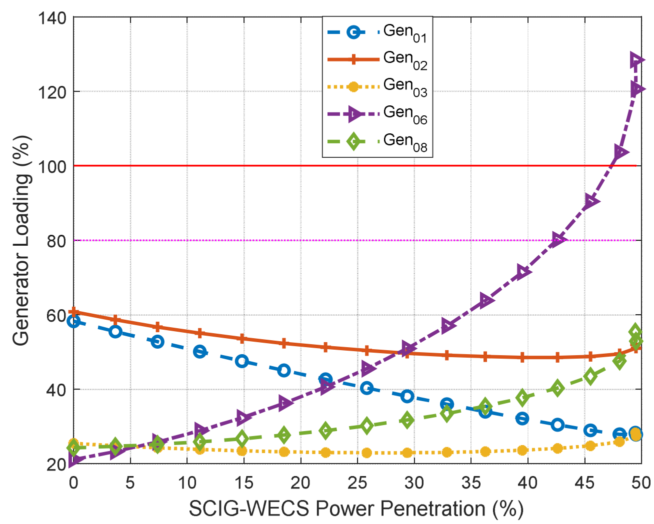

Fig. 5 Loading Effect on the Generators

2) Transformers: Fig. 6 illustrates the influence of increased SCIG-WS integration on loading of transformers. The figure shows that none of the transformers is considerably affected by increasing SCIG-WS power penetration. A maximum loading of about 69.4% was obtained for Transformer 7-9 at the maximum penetration level of 49.45% This implies that transformer loading does not present any limiting factor for increasing SCIG-WS power penetration for the 14-bus case study.

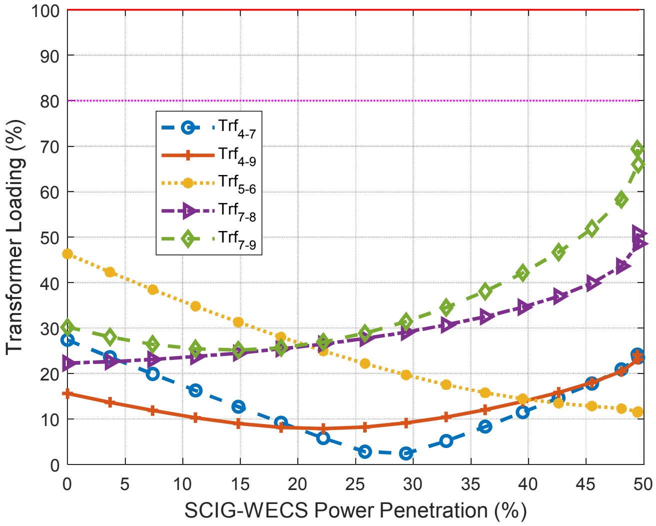

Fig. 6 Loading Effect on the Transformers

3) Transmission Lines: The influence of increased SCIG-WS integration on the loading of transmission lines is illustrated in Fig. 7. The figure reveals that three lines, namely, Line 9-14, Line 13-14 and Line 6-13 are significantly affected by increasing SCIG-WS power penetration. At maximum penetration level of 49.45%, Line 9-14 loading is 201.1%, Line 13-14 loading is 162.5%, and Line 6-13 loading is 129.65%. The remaining lines have their loadings less than 56% at all PLs. Line 9-14 attains 80% at SCIG-WS PL of 28.3%, and 100% at 33.73% PL; Line 13-14 attains 80% and 100% loading at 34.45% and 40.58% SCIG-WS PL respectively. Also, Line 6-13 attains 80% at SCIG-WS PL of 41.47%, then 100% at 46.7% PL. These values are the limits for SCIG-WS integration.

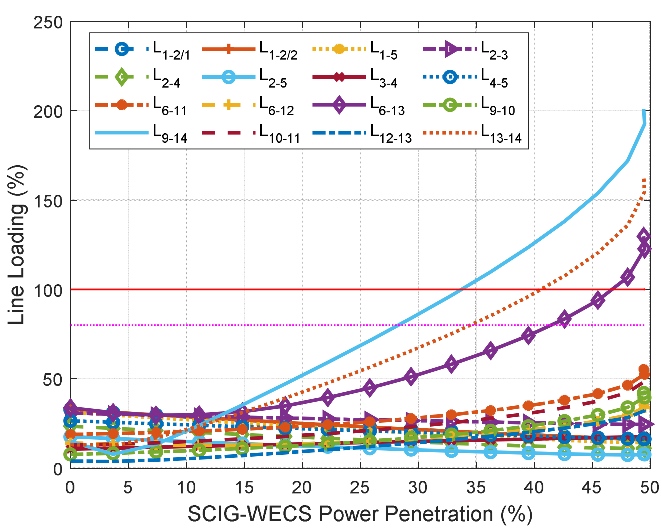

Fig. 7 Loading Effect on the Transmission Lines

The analysis above shows that increased SCIG-WS integration has considerable influence on system elements, particularly the transmission lines. Therefore, the permissible SCIG-WS PL is 33.73% (92.58MW). This is the loading limit for Line 9-14. If higher SCIG-WS PLs is to be obtained, then reactive power compensation and system expansion is necessary.

IV. Reactive VAR Compensation with SVS

In order to enhance the loading limits of the system with increased SCIG-WS integration, a 30MVAR SVS is located at bus 14 for a PL of 33.73% (92.58MW).

The λ-V curve of the weakest bus with and without SVS application is depicted in Fig. 8. The figure indicates that the SVS can enhance λ_{max} from 2.053 to 3.583 denoting a megawatt margin increase from 531.7MW to 927.9MW, which is about 74.51% increase in loadability of the system. Also, with the application of SVS at bus 14, the loading of the most critical element, which is Line 9-14 reduces from 100% to 90.3%. This is because the SVS is able to inject additional reactive power into the grid system. Furthermore, there is an appreciable reduction in the active and reactive power losses of the system. The active power loss reduced from 15.37MW to 13.19MW while the reactive power loss reduced from 23.13MVAR to 16.97MVAR.

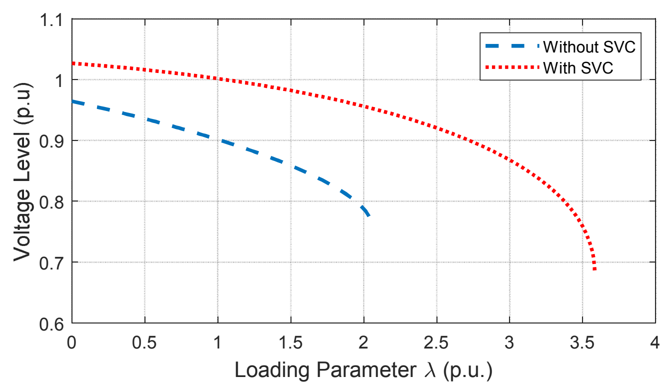

Fig. 8 λ-V Curve for the Weakest Bus with and without SVS

V. Conclusion

Voltage stability analysis of power system with increased SCIG-WS integration has been examined in this paper. Static analysis based on λ-V curve has been employed to obtain the loadability limits of the power system as the SCIG-WS PL increases. In addition, the resulting influence of increased SCIG-WS integration on system element loading have been examined. The results show that without reactive VAR compensation strategy, the loadability limits of the system diminishes with increased SCIG-WS PL. Also, significant increase in SCIG-WS PL affects the system element loading considerably. To avoid system element overloading, the maximum allowable SCIG-WS PL for the test system used is 33.73% as determined by the loading limit of Line 9-14, which is the most critical element. The system's voltage stability can be enhanced with the use of SVS placed at the most critical bus. In this study, SVS was placed at bus 14 and the outcome indicates that λ_{max} improved by about 74.51%. Moreover, there is significant reduction in grid losses as well as reduction in the loading of the most critical network element.

VI. Acknowledgement

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