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STUDY ON SYSTEM STRENGTH OF THE POWER GRID WITH PENETRATION OF RENEWABLES

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Abstract

The global demand for renewable energy presents the trend of accelerating growth in recent years due to depletion of fossil fuels and potential environmental problems. Integration of geographic dispersed renewable energy sources (RES) into a power system focuses on the incorporation of such kind of sources in a reliable and economic way while maintaining the grid integrity, reliability and load deliverability. However, increasing penetration of power electronic converter (PEC) based RES such as wind, solar and battery storage plants equipped with fast-acting control systems to the weak points of a power system could alter the system characteristics and challenge equipment manufacturers, system planners and operators [1]. This challenge comes from the fact that connecting these RES to the weaker portions of the system may result in potential issues related to voltage stability and quality. In the worst conditions, such system stability issues could be wide-spread and lead to loss of generation and/or damage of RES equipment if the protection measures are not adequately implemented.

System strength is one of the important concerns in the integration of RES. The strength of a power system at the point of interconnection (POI) of RES can be regarded as the ability of a system to maintain its voltage stability and quality. Recently, short circuit ratio (SCR) has been used to evaluate the system strength at the POI of RES. However, this commonly used method does not consider the interactions among RES, which may lead to an overly-optimistic result. To account for the effect of such interactions on the

system strength, several improved methods were developed, such as weighted SCR (WSCR) proposed by ERCOT and composite SCR (CSCR) proposed by GE. But the WSCR and CSCR methods do not take into consideration the real electrical connections among RES, which may not reflect the actual system strength at each individual POI of RES. To overcome the defeats in previous three methods, site-dependent SCR (SDSCR) has been proposed, this new method can not only be used to evaluate the system strength in terms of the distance to voltage stability limit, but also reflect the system strength at each individual point connected to RES.

In this thesis, a number of studies are conducted to demonstrate the efficacy and accuracy of SDSCR method in various applications. To validate the efficacy of SDSCR method, a simulated comparison of this new method with other three methods with respect to voltage stability limit was implemented. Moreover, several studies related to applications of SDSCR method were designed, the accuracy of this method was further validated in transfer capability calculation and it also be used to investigate the impact of grid structure on system strength. Finally, a designed procedure for cascading line outages was employed using different perspective to identify the weakest area in a system and compare the results with that obtained by system strength evaluation.

The results of the studies suggest that SDSCR method can effectively evaluate the system strength at each individual point connected to RES in terms of the distance to voltage stability limits. Also, this new method can accurately estimate the transfer capability without compromising the lower voltage limit under normal operating conditions.

Chapter 1 Introduction

Today the use of renewable energy technologies to provide electricity, heating and cooling, and transportation is now spread across the globe, and the latest trends suggest sustained growth worldwide. The fast development of renewable energy attributes to the potential environmental problems and rapid growth of population. Problems associated with the environment not only related to global warming, but also to such environment concerns as air pollution, acid precipitation, ozone depletion, forest destruction, and emission of radioactive substances [2]. Also, the population plays an essential role in impending energy shortage. As populations grow, many faster than the average 2%, the demand for more and more energy is aggravated. Enhanced lifestyle and energy demand rise together and the wealthy industrialized economies which contain 25% of the world's population consume 75% of the world's energy supply [3]. Thus, accelerating the deployment of renewable energy will effectively alleviate the problems mentioned above to some extent. Though increasing the percentage of renewable energy is necessary and immediately, integration of RES into a power system still exists some challenges and problems. Renewable and distributed resources introduce location and time constraints on resource availability. Wind and solar energy as two main renewable sources, which have intrinsic characteristics of variation and uncertainty, that is, they only produce energy when the wind is blowing or the sun is shinning. Such intermittent nature will lead to reliability issues and provide the difficulty to system planners and operators. Moreover, the locational impact of renewable sources cannot be ignored. Most of the renewables installed at load zone, far from the main gird, the strength of points connected to these RES are weak, so the voltage issues related to stability and quality are more likely to occur.

Some methods were proposed to examine the system strength of a power system at the POI of RES. The commonly used one is short circuit ratio (SCR), however, this method does not consider the interactions among RES, so the estimated result may overly-optimistic. To overcome this shortage, some advanced methods were developed, such as weighted short circuit ratio (WSCR) and Composite short circuit ratio (CSCR) with the consideration of interactions among RES. But the WSCR and CSCR methods do not take into consideration the real electrical connections among RES, which may not reflect the actual strength of the system at each individual point of the interconnection of RES. To overcome the defeats in previous three methods, the site-dependent short circuit ratio (SDSCR) has been proposed, and its efficacy, accuracy and applications will be conducted in the later Chapters.

Section 1.1 Background: Development of Renewable Energy

Renewable energy is a fundamental and growing part of the world's ongoing energy transformation. The global demand for renewable energy presents the trend of accelerating growth for the past decade. In fact, global installed capacity and power generation increased dramatically and there has been an increasing trend of renewable energy investments and supporting policies since the early 2000s. The various energy crises, economic issues in recent years and people increased attention to the climate change have been the major factors in this rapid development. Moreover, some pioneer countries in the field of renewables, such as Germany, Denmark and Spain, created early markets for renewables, which laid the foundation for the technical advances and market expansion [4].

Wind and solar energy as representative of renewable sources have been witnessed for the rapid development over the past decade. Wind power saw an extraordinary increase moving from a total installed capacity of 48GW in 2004 to 318GW in 2014. High competition and technology improvements lead to the falling prices of wind power, and it is considered as a feasible and economic energy compared with heavily subsided fossil fuels in markets. Solar PV saw a similar increase, grew by a factor of 70, from 2.6GW to 139GW [4].

In 2015, the contribution of all renewable sources experienced its largest annual increase in energy capacity, with an approximately 147 GW of renewable capacity added. Total global capacity was up almost 9.3% over 2014, to an estimated 1,849 GW at the end of the year. Moreover, wind and solar PV both saw record additions for the second consecutive year, together making up about 77% of all renewable energy capacity added in 2015 [5], indicating an increasing demand of renewable energy capacity.

Global perceptions of renewable energy have changed considerably and renewable energy technologies gradually moved into the mainstream. By 2030, the global share of renewables is expected to be doubled compared with 2010. However, high penetration of renewables into a power system still exists some challenges and issues, which should be tackled to achieve a compatibility between a designed power system and distributed RES.

Section 1.2 Grid Integration of Renewable Energy: Challenge and Key Issues

The challenge and issues related to high penetration of renewables mainly stem from following aspects: the intermittent nature of renewables, the fast dynamic response from PEC within the renewable generation plants and location of renewables. The intermittent nature refers to uncertainty and variability of RES normally due to characteristic weather fluctuations. Solar PV is highly dependent on the sunshine, the presence of clouds that can pass over the solar power plants and limit generation for short periods of time. Cloud cover can lead to a rapid change in the output of individual solar PV, but the impact on power grid could be minimized if these solar PVs are spread out and geographically dispersed so that they are not influenced by clouds at the same time. Compared with solar, wind energy is subject to daily and seasonal weather patterns. Typically, the wind blows stronger at nighttime or in the winter, so the wind energy is more available at these time slots [6][7]. The intermittent nature of renewables brings the difficulty to the system operators. Since the operators need to make sure that they have sufficient resources to accommodate the significant changes in renewable generation to maintain the system balance.

The RES, such as wind, solar and battery storage plants are connected to power systems through PEC controllers. The voltage/reactive power control loops within these RES are capable of providing almost instantaneous reactive power injection in response to the voltage change at the POI. Such fast dynamic response could result in a high sensitivity of voltage with respect to reactive power, a small change of reactive power will lead to a large oscillation in voltage [8]. Therefore, the speed of the voltage controllers associated with RES has a substantial impact on the stability of the interconnected grid. When a large amount of RES are connected to weak points of a power system, undesired system stability issues, especially those related to voltage stability and quality may be exposed and result in serious consequence. In the worst condition, such system stability issues could be wide-spread and lead to loss of generation and/or damage of RES equipment if the protection measures are not adequately implemented.

The location of RES is another problem should be concerned. For the RES installed at distribution networks, they are usually located in remote regions, far from the main grid. Placing the renewables distant from the main grid can cause the problems when controlling the quality of power injected to the grid [9]. Moreover, the POIs of these RES are usually weak, so the voltage stability issues are more likely to occur in case of variation of reactive power.

Section 1.3 Overview of Current Solutions

Based on the impact of integration of RES into weak portions of a power system, some methods were developed and employed for evaluation of system strength at the POIs of RES.

The commonly used one is short circuit ratio (SCR), which has been applied to the development as an indicator of system strength. It reflects the stiffness of a network bus with respect to the rated power of an interconnected RES. The calculated value of SCR can be used to identify the weak areas in a power system, in which compensation measures and further monitoring are required to against potential system stability issues. However, in the practical situations, the estimated results obtained by SCR method is not accurate since it does not consider the interactions from nearby power plants. To account for such interactions, several new methods were developed, such as composite short circuit ratio (CSCR) proposed by GE and weighted short circuit ratio (WSCR) proposed by ERCOT. With the consideration of interactions among RES, these two advanced methods can perform a relatively more precise assessment of system strength with high penetration of RES in a power system. However, the CSCR and WSCR methods do not consider the real electrical connections among RES, which may not reflect the actual system strength at each individual POI of RES.

Section 1.4 Motivation of the Study

Large-scaled integration of RES into a power system could change the system characteristics, especially influence the voltage performance under normal operating conditions and cause undesired system stability issues related to voltage stability and quality. Therefore, it is necessary to examine the system strength at the POIs of RES.

So far, several methods were developed with a focus on system strength evaluation. However, each of them has limitation and cannot truly reflect the actual system strength at each POI of RES. So, it is imperative to develop a new method to evaluate the system strength at the POIs of RES with the consideration of interactions among them characterized by the real electrical connectivity. Thus, SDSCR method has been proposed for this reason. This new method can assess the system strength in terms of the distance to voltage stability limits. Moreover, it takes into consideration the effect of interactions among RES on system strength according to real electrical connections among them in a power system.

The main motivation of this study is to validate the efficacy and accuracy of SDSCR method in assessing the impact of RES on system strength compared with SCR, CSCR and WSCR methods. Besides, several studies related to applications of this new method were conducted to further demonstrate its precision and feasibility in practical problems.

Section 1.5 Description and Summary of the Study

The study mainly focuses on assessing system strength at the POI of RES by some SCR-based methods. On the basis of commonly used SCR method with single RES in a power system, the SDSCR method is derived and incorporated by the factor of real electrical connection with the consideration of multiple RES in the system. Then, the efficacy and accuracy of SDSCR method are validated through numerical simulation with SCR, CSCR and WSCR methods under base case and contingency case. Based on the validation of SDSCR method, this new method is used to investigate the impact of grid structure on system strength, more specifically, explore the impact of transformer and generator's locations on system strength and explain the sensitivity of the grid structure.

Moreover, the accuracy of SDSCR method is further validated through an application in transfer capability calculation with geographic dispersed RES. A modified procedure for transfer capability calculation is designed, the core ideal of this proposed procedure is to identify the renewable generation limits with respect to the threshold values of SCR-based methods. In addition, the locational impact of RES on transfer capability is also investigated by SDSCR method and P-V analysis. Finally, a three-step approach for cascading line outages is proposed to identify the weakest areas in the power system, the simulated results are compared with the one obtained by SDSCR method.

This document is organized as follows. The commonly used SCR method, its relationship between some power system properties as well as its limitation are elaborated in Chapter

2. Chapter 3 gives a presentation of two advanced SCR-based methods, CSCR and WSCR methods. In Chapter 4, the SDSCR method is proposed by a detailed deduction, after that, a numerical study is conducted to validate the efficacy and accuracy of this new method. Chapter 5 describes an application of SDSCR method in the investigation of the impact of grid structure on system strength. Chapter 6 is another application of SDSCR method in transfer capability calculation with the integration of RES. Chapter 7 proposes an approach of cascading line outages and how it be employed for weakest area identification. Finally, the document culminates with the conclusions and future work.

Chapter 2 Current SCR-Based Methods for System Strength Evaluation

System strength is an inherent characteristic of any electric power systems and it is highly relative to the ability of the system to maintain the stability and quality of bus voltages at the POIs of RES in terms of the disturbances. System strength has great significance to the system performance since it will affect the way of a power system operates. Thus, it is useful to have a simple method of measuring and comparing the relative strength of an AC system. The short circuit ratio (SCR) has evolved as such a measure. The SCR method is well developed and trusted for integration of single RES in the power system, it is not well suited for areas with multiple RES in close proximity. For such cases, the industry is moving towards to new methods with the consideration of interactions among RES. Thus, two advanced SCR-Based has been proposed and employed by the power industries for system strength evaluation with multiple RES recently. They are Weighted SCR (WSCR) developed by ERCOT and Composite SCR (CSCR) developed by GE. Compared with commonly used SCR calculation method, these two advanced methods incorporated by the effect of interactions among RES in their calculations which can give a more accurate estimation of system strength with high penetration of RES in a power system. However, the limitations of these two methods cannot be ignored. Since they manifest the effect of interactions among renewables by simple weighted arithmetic without considering the real electrical connection among RES, which may not reflect the actual system strength at each individual point of the interconnection of RES.

To this end, the relationship between system strength and SCR is elaborated at first. There are two versions of SCR for system strength evaluation. The original one is used for HVDC systems, another one is an extended version which is applied to the renewable systems. Then, the relationship between SCR and voltage stability is expounded. After that, the WSCR and CSCR methods are introduced in detail. Finally, the limitations of commonly used SCR, CSCR and WSCR methods are identified and summarized, which raises the development of a new method, Site-Dependent SCR method in Chapter 3.

Section 2.1 Short Circuit Ratio

Short circuit ratio is an indicator of the system strength, which is defined as the ratio of system short circuit level MVA to the rated power MW of the interconnected device [10]. The SCR is used to quantify the strength of the power system at the POI of the device. The strength of a power system at the POI of the device can be considered as the ability of the system at the point to maintain its voltage stability and quality. In this section, the concept of SCR and its relationship between some power system properties are elaborated. In 2.1.1, the relationship between SCR and system strength is explained. In 2.1.2, the relationship between SCR and voltage stability is established.

Section 2.1.1 Short Circuit Ratio and System Strength

System strength is one of the important concerns with respect to the connection of power electronic converter based devices on power systems. The performance of various components in a power system depends on the system strength, which reflects the sensitivity of system variables to various disturbances. The strength of a power system at the POI of the device can be regarded as the ability of the system to maintain its voltage stability and quality at that point. Since the system strength has a very significant impact on the system performance, it is useful to have a simple method of measuring and comparing the relative strength of the power system. Thus, the short circuit ratio (SCR) has evolved as an indicator of system strength, it is defined as the ratio of system short circuit capacity MVA to the rated power MW of the interconnected device [11]. The point of a power system is strong defined as having an SCR above three, and the SCRs of weak and very weak points range between three and two and below two, respectively.

SCR was originally used to analyze the impact of the AC/DC system interactions on the AC system strength. For an HVDC converter connected to AC systems, the interaction between the AC and DC systems can be parameterized by the strength of the AC system at the POI to that of the DC system [12]. The SCR is used to quantify the strength at the POI of HVDC converter and its value determines how strong the AC system at that bus to support the stable operation of HVDC converter connected to it. Specific levels of SCR are required to maintain the stable operation of HVDC converters in AC/DC systems [13].

Recently, according to the demands of clean energy, high reliability and power quality for sensitive loads, the demand of renewable generation sources is gradually rising. Unlike conventional sources, the power generated in renewable generation sources such as fuel cells, microturbines, solar cells and wind turbines is DC, which is used as the input to an inverter which ultimately interfaces with the AC system network. Like HVDC converters, specific levels of SCR are required to support stable operation of these renewable generation sources. Moreover, the renewable generation sources can either be grid connected or independent of the grid. For those connected to the grid are typically interfaced at the distribution systems, far from the main grid. The points of interconnection of these renewable generation sources are weak, and voltage stability issues are more likely to occur [14][15]. Therefore, it is necessary to measure the system strength at all possible interconnected points. Also, the RES has some similar architecture and operational mechanism compared with HVDC devices, so the commonly used SCR now has been extended and employed to quantify the strength at the POI of RES. The SCR at bus i can be represented as

$$SCR_i = \frac{S_{ac,i}}{P_{d,i}} = \frac{|V_i|^2}{P_{d,i}} \cdot \frac{1}{|Z_i|} \tag{1}$$

Where $S_{ac,i}$ is the short circuit capacity of the system at bus i; $P_{d,i}$ is the rated power MW of the RES connected to bus i; $|V_i|$ and $|Z_i|$ are the voltage magnitude and magnitude of Thevenin equivalent impedance at bus i respectively.

According to the formula of SCR, the system strength is highly dependent on the short circuit capacity and interconnected RES at a specific point. The short circuit capacity is defined as the product of the magnitude of pre-fault bus voltage and fault current. Typically, higher fault current levels are identified closer to the synchronous generations because of the reduction of the Thevenin equivalent impedance seen at system buses and the strength of these buses are considered strong. As a contrast, the fault current levels decreased when the positions further away from synchronous generation and the corresponding buses are considered as weak. A higher fault current level can be regarded as a strong response of the generation in a power system, which produces a higher current flowing to the faulted position with respect to the voltage drop at that point. Similarly, the SCR value indicates the strength of a bus relates to the response of the faults at that bus.

Moreover, the system strength also depends on the amounts of power electronic based generations. So, the strong buses in a power system indicated by large SCR values have the characteristics of a high quantity of synchronous generations and very little power electronic based generators such as renewable generation sources. Furthermore, such kind of power system contributes higher levels of fault current and more prone to maintain a stable operation during the disturbance conditions.

Section 2.1.2 Short Circuit Ratio and Voltage Stability

Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under the normal operating condition and after being subjected to disturbance [16].

Short circuit ratio is a metric which can be used to evaluate the system strength of a bus connected to RES. The strength of a bus can be defined as the ability of a bus to maintain its voltage level with respect to the injections of reactive power at that bus. Generally, the bus in a power system with a high SCR will experience less much voltage variation compared with a bus having a lower SCR. For a bus which is infinitely strong or has infinitely short circuit capacity, will have zero equivalent impedance. Such a bus is easy to keep constant voltage level despite the disturbances. Therefore, even though the SCR is calculated using steady-state values, its value is a measure of how easily bus voltages are affected during the dynamic system events.

Section 2.2 Weighted Short Circuit Ratio (WSCR)

To take into consideration the effect of interactions among RES and therefore to give a more precise evaluation of system strength at the POI of RES, a more appropriate method weighted SCR has been proposed by ERCOT. The WSCR method is defined by

$$\begin{aligned} \mathrm{WSCR} &= \frac{Weighted\ S_{SCMVA}}{\sum_i^N P_{RWMi}} \\ &= \frac{(\sum_i^N S_{SCMVAi} * P_{RMWi}) / \sum_i^N P_{RMWi}}{\sum_i^N P_{RMWi}} \\ &= \frac{\sum_i^N S_{SCMVAi} * P_{RMWi}}{(\sum_i^N P_{RMWi})^2} \end{aligned} \tag{2}$$

where S_{SCMVAi} is the short circuit capacity at bus i before the connection of RES i at that bus; P_{RMWi} is the rated power MW of RES i to be connected; N is the total number of RES fully interacting with each other and i represents for the index of RES [17].

This calculation method is based on the assumption of full interactions between RES in a given area. It is equivalent to assuming all RES are connected to a single POI. In practical situations, there is some electrical distance between POIs and all the RES are not fully interacting with each other. Thus, the system strength evaluated by WSCR method is kind of conservative. On the other hand, a minimum WSCR of 1.5 is required to ensure the voltage stability and to provide some stability margin. The system strength at POI of RES calculated by WSCR method is much smaller than the one obtained by SCR method, which implies that renewable generation sources interact with each other and actual system strength is weaker compared with the condition that each of them oscillates individually.

Section 2.3 Composite Short Circuit Ratio (CSCR)

CSCR is an indicator of system strength which is applied to characterize the ability of a power system to maintain its stable operation with the connection of PEC-based sources. It has been proposed by GE and defined as the ratio of the composite short circuit capacity MVA at the POI of all RES in a given area to the combined rated capacity of all these RES [18]. The expression of CSCR is given by

$$\mathrm{CSCR} = \frac{Composite_{SCMVA}}{\sum RES_{MW\ Rating}} \tag{3}$$

Like WSCR, CSCR accounts for the effect of multiple nearby RES by taking the ratio of composite short circuit capacity to that total rated capacity of all RES. The composite short circuit capacity is calculated by selecting a bus in a power system which is relatively close to the POI of RES, creating a “composite” bus. The short circuit capacity is then calculated at that bus through normal fault calculation methods. A system with a higher CSCR considered to be strong and a system with a lower CSCR considered to be weak. Conventionally, a strong system usually has a CSCR value approximately about 2.5 to 3 and CSCR value below about 1.7 to 1.5 is considered as weak. In the worst conditions, some additional measures must be taken if the CSCR value below 1.0.

Section 2.4 Limitations of SCR-Based Methods

Even though the SCR calculation method is commonly accepted and used for evaluation of system strength at the POI of RES, it ignores the interactions among these renewables. For some system conditions, the electrical distances between these RES are small, they will interact with each other and oscillate together like a single huge unit. In such cases, the interactions affect the strength of the power system at the POI of RES and this commonly used SCR method may give an overly optimistic estimation of system strength at the POI of RES.

To take into account the effect of such interactions on system strength, the WSCR and CSCR methods were developed. Although WSCR and CSCR methods can mitigate the effect of ignorance of interactions among RES to some extent compared with commonly used SCR method, these two methods still exist some limitations which will affect the accurate measurement of system strength at the POI of RES. The limitations of WSCR and CSCR methods can be summarized as follows.

WSCR calculation method is conducted based on the assumption that each renewable generation plant is fully interacts with each other. However, in most of the practical circumstances, the RES are not connected to the same POI and there is usually some electrical distances between different POIs. So, the RES are not fully interact with each other and the system strength evaluated by WSCR method is much more conservative than the true one. The actual system strength is between the value obtained by WSCR method and commonly used SCR method. Moreover, WSCR method may not reflect the actual system strength at each individual point of the interconnection of RES due to the disregard of real electrical connections among these RES.

Like WSCR method, the CSCR method also does not take into consideration the real electrical connections in its calculation, which may not accurately measure the system strength at each individual point of the interconnection of RES. Besides, the significant feature of CSCR method is that the estimated result of system strength is highly dependent on the choice of the composite bus in a power system. Therefore, the system strength calculated by CSCR method could be misleading.

Last but the most important, voltage stability is one of the main concerns with respect to the integration of a large amount of RES at the weak portions of a power system. But the SCR, CSCR and WSCR methods do not clearly explain the relationship between system strength and voltage stability in their definitions.

Section 2.5 Chapter Summary

This Chapter introduces the commonly used SCR method, especially explain the relationships between SCR and some power system properties such as system strength and voltage stability. Previously, the SCR method was used to evaluate the impact of the AC/DC system interactions on the AC strength. Due to the similarity between HVDC device and PEC based renewable generation plant, the SCR method is recently used to assess the system strength at the POI of RES. However, this method ignores the interaction among RES, which will lead to an overly optimistic result. To overcome this limitation, the WSCR and CSCR methods were developed. These two methods are regarded as an advanced version of commonly used SCR method, which is recognized by the power industries for system strength evaluation with high penetration of RES. However, the defect of ignorance of real electrical connections among RES leads to these two methods kinds of inaccurate. To account for the factor of real electrical connections among RES, a new method, Site-Dependent Short Circuit Ratio will be proposed and validated in the next Chapter.

Chapter 3 New Proposed SDSCR Method for System Strength Evaluation

In this Chapter, Site-Dependent Short Circuit Ratio (SDSCR) will be derived and validated by numerical simulations on IEEE 39-bus test system [19]. From Chapter 2, the limitations of commonly used SCR, WSCR and CSCR methods were identified. The SDSCR method is proposed to remedy the defects of these SCR-based methods. First, the relationship between static voltage stability and system strength is analyzed in a power system with a single renewable generation plant. Then the analytic result is expanded to the situation with multiple renewable generation plants in the system to derive the prototype of SDSCR method. The real electrical connections among RES are incorporated in the concept of SDSCR method based on the geographic dispersed RES in the power system.

To validate the efficacy and accuracy of this newly developed SDSCR method, it is compared with SCR, WSCR and CSCR methods through numerical simulations in terms of the distance to the static voltage stability limit at the POI of RES under base case and contingency case. With the auxiliary of P-V analysis, the stability boundary of renewable generation sources is determined by the further selection of power system operating conditions. The numerical simulations are conducted based on these sets of operating conditions. The results of the numerical study suggest that SDSCR methods can accurately quantify the system strength in terms of the distance to the static voltage stability limit under both cases. The SCR and CSCR methods overestimate the system strength at the POI of RES while the estimated results of WSCR method is conservative. Therefore, the efficacy and accuracy of SDSCR method are successfully demonstrated.

Section 3.1 Derivation of SDSCR Method

The derivation of SDSCR method is based on the properties of commonly used SCR method, especially establish the relationship between the system strength and static voltage stability with a single renewable generation plant in a power system at the preliminary step, which has not been covered in other people's research work. Then the factor of real electrical connection among RES is incorporated by the consideration of multiple geographic dispersed renewable generation sources in the system to further derive SDSCR method.

In Figure 1, a sketch of AC power network with the integration of single renewable generation source is presented. The whole system can be simplified to an equivalent two-bus system which is shown in Figure 2. In the equivalent system, the power equation can be represented as follow

$$\frac{V_i - V_s}{Z_i} = I_i = \left(\frac{S_i}{V_i}\right)^* \tag{4}$$

where V_i and V_s are the voltages at buses i and s respectively; Z_i is the Thevenin equivalent impedance at bus i; S_i is the complex power injected from the renewable generation source.

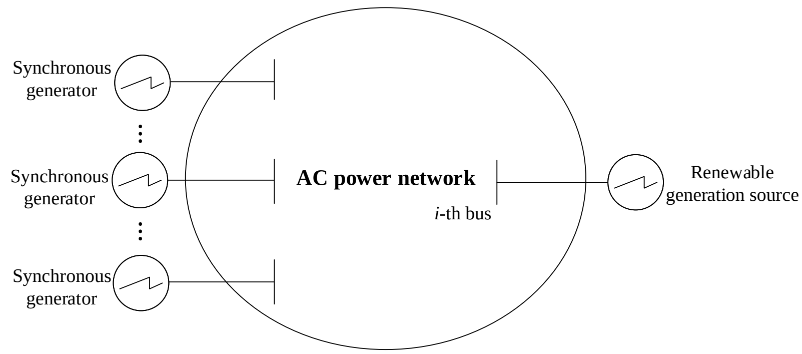

Figure 1. An AC power system with a single renewable generation source

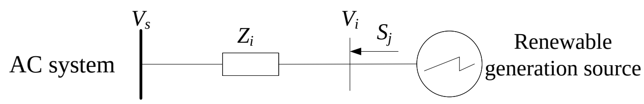

Figure 2. Two-bus equivalent system of AC power system with a single renewable generation source

Rearrange the equation (5) as follow

$$Z_i S_i^* = |V_i|^2 - V_s V_i^* \tag{5}$$

Since the complex number is contained in equation (6), so let $Z_i S_i^* = a - jb$, where a and b are two real numbers, so the above equation can be decomposed as follow

$$\mathrm{a} = |V_i|^2 - |V_s||V_i| \cos \theta_{si} \tag{6}$$

$$\mathrm{b} = |V_s||V_i| \sin \theta_{si} \tag{7}$$

where $|V_i|$ and $|V_s|$ are the voltage magnitudes at bus i and s respectively; θ_{si} is the angular difference between these two bus voltages and $\theta_{si} = \theta_s - \theta_i$

Suppose $|V_s|$ is a constant, then a and b are the functions of $|V_i|$ and θ_{si}

$$\mathrm{a} = f_1(|V_i|, \theta_{si}) = |V_i|^2 - |V_s||V_i| \cos \theta_{si} \tag{8}$$

$$\mathrm{b} = f_2(|V_i|, \theta_{si}) = |V_s||V_i| \sin \theta_{si} \tag{9}$$

Now, consider the Jacobian matrix for functions f_1 and f_2

$$\mathrm{J} = \begin{bmatrix} \frac{\partial f_1}{\partial |V_i|} & \frac{\partial f_1}{\partial \theta_{si}} \\ \frac{\partial f_2}{\partial |V_i|} & \frac{\partial f_2}{\partial \theta_{si}} \end{bmatrix} = \begin{bmatrix} 2|V_i| - |V_s|\cos\theta_{si} & |V_s||V_i|\sin\theta_{si} \\ |V_s|\sin\theta_{si} & |V_s||V_i|\cos\theta_{si} \end{bmatrix} \tag{10}$$

The critical condition of voltage stability at bus i occurs when J is singular, that is, the determinant of J is equal to zero. Thus

$$\frac{2|V_i|\cos\theta_{si}}{|V_s|} - 1 = 0 \tag{11}$$

Rearrange equation (11) get

$$\frac{|V_i|\cos\theta_{si}}{|V_s|} = \frac{1}{2} = Re\left[\frac{V_i}{V_s}\right] \tag{12}$$

where $\frac{V_i}{V_s} = \frac{1}{2} + jc,$ c is a real number.

Substitute equation (5) into (12) get

$$\frac{Z_i S_i^*}{|V_i|^2} = 1 - \frac{V_s}{V_i} \tag{13}$$

Rewrite equation (13) get

$$\left|\frac{Z_i S_i^*}{|V_i|^2}\right| = \left|1 - \frac{V_s}{V_i}\right| = \left|1 - \frac{1}{\frac{1}{2} + jc}\right| = 1 \tag{14}$$

From equation (14), the ratio at bus i with respect to the critical condition of voltage stability is obtained as follow

$$r_i = \left|\frac{1}{Z_i S_i^*}\right| \cdot |V_i|^2 = \frac{|V_i|^2}{|Z_i S_i^*|} = \frac{|S_{ac,i}|}{|S_i^*|} = 1 \tag{15}$$

According to (15), the voltage instability at bus i occurs if the short circuit capacity $|S_{ac,i}|$ is smaller than the injected power at that bus and the ratio r_i is less than 1. Conversely, if the ratio r_i is larger than or equal to 1, the voltage at bus i is stable.

Compare the expression of SCR_i in equation (1) and the ratio r_i in equation (15). These two equations are the same when the injected power S_i in (15) is replaced by the rated capacity of RES $P_{d,i}$. Then

$$SCR_i = r_i = \frac{|S_{ac,i}|}{P_{d,i}} = \frac{|V_i|^2}{P_{d,i}|Z_i|} \tag{16}$$

Equation (16) shows that commonly used SCR method can quantify the system strength in terms of the distance to the static voltage stability limit. Normally, a higher SCR value indicates the strong system at the POI of RES since there is more distance from bus voltage to its stability limit. Otherwise, the strength at the POI of RES becomes weaker when the bus voltage approaches to its stability limit.

In most practical situations, multiple renewable generation sources are integrated into the power system and interact with each other when they are electrically close. Similar to the situation with single RES integration, the relationship between system strength and static voltage stability with multiple RES is analyzed at first. Then the SDSCR method is derived by incorporating the real electrical connection among RES. Figure 3 depicts an AC power system with the connection of multiple renewable generation sources.

Write the network equation for the system in Figure 3 as follow

$$\begin{bmatrix} \boldsymbol{V}_G \\ \boldsymbol{V}_R \end{bmatrix} = \begin{bmatrix} \boldsymbol{Z}_{GG} & \boldsymbol{Z}_{GR} \\ \boldsymbol{Z}_{RG} & \boldsymbol{Z}_{RR} \end{bmatrix} \begin{bmatrix} \boldsymbol{I}_G \\ \boldsymbol{I}_R \end{bmatrix} \tag{17}$$

where $\boldsymbol{V}_G$ and $\boldsymbol{V}_R$ are the voltage vectors of buses connected to synchronous generators and RES, respectively; $\boldsymbol{I}_G$ and $\boldsymbol{I}_R$ are the vectors stand for the currents injected to the buses connected to synchronous generators and RES; $\boldsymbol{Z}_{GG}$, $\boldsymbol{Z}_{GR}$, $\boldsymbol{Z}_{RG}$ and $\boldsymbol{Z}_{RR}$ are corresponding portions of bus impedance matrix.

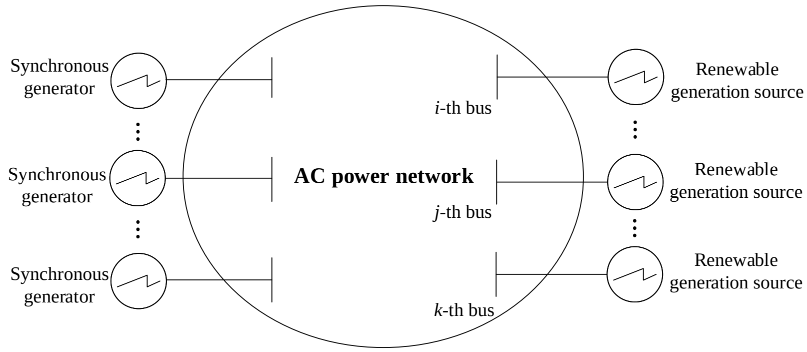

Figure 3. An AC power system with multiple renewable generation sources

The critical condition of voltage stability at bus i with the connection of renewable generation source is concerned, the voltage at bus i can be written as below based on (17).

$$V_{R,i} = \sum_{k \in G} Z_{RG,ik} I_{G,k} + \sum_{j \in R} Z_{RR,ij} I_{R,j}$$

$$= \sum_{k \in G} Z_{RG,ik} I_{G,k} + Z_{RR,ii} \sum_{j \in R} \frac{Z_{RR,ij}}{Z_{RR,ii}} I_{R,j} \quad (18)$$

where $V_{R,i}$ is the i^{th} element in voltage vector for the buses that connected to RES; $Z_{RG,ik}$ is the $(i, k)^{\text{th}}$ element in matrix $\boldsymbol{Z}_{RG}$ and $Z_{RR,ij}$ is the $(i, j)^{\text{th}}$ element in matrix $\boldsymbol{Z}_{RR}$; $I_{G,k}$ and $I_{R,j}$ are the k^{th} and j^{th} element in current vectors $\boldsymbol{I}_G$ and $\boldsymbol{I}_R$, respectively. $\boldsymbol{G}$ and $\boldsymbol{R}$ are the sets of all buses that connected to the synchronous generators and RES, respectively.

Reconsider the two-bus equivalent system in 4.1.1, write the power equation as below

$$\frac{V_{R,i} - V_{S,i}}{Z_{RR,ii}} = I_{eq,i} = \left(\frac{S_{eq,i}}{V_{R,i}}\right)^* \quad (19)$$

where

$$V_{S,i} = \sum_{k \in G} Z_{RG,ik} I_{G,k} \quad (20)$$

$$I_{eq,i} = \sum_{j\in R} \frac{Z_{RR,ij}}{Z_{RR,ii}} I_{R,j} = I_{R,i} + \sum_{j\in R, j\neq i} \frac{Z_{RR,ij}}{Z_{RR,ii}} I_{R,j} \tag{21}$$

Consider the complex power $S_{eq,i}$ injected to bus i in two-bus equivalent system

$$S_{eq,i} = V_{R,i} I^*_{eq,i} = V_{R,i}\left(I^*_{R,i} + \sum_{j\in R, j\neq i} \frac{Z^*_{RR,ij}}{Z^*_{RR,ii}} I^*_{R,j}\right) = \left(S_{R,i} + \sum_{j\in R, j\neq i} \frac{Z^*_{RR,ij}}{Z^*_{RR,ii}} \cdot \frac{V_{R,i}}{V_{R,j}} S_{R,j}\right) \tag{22}$$

According to equation (22), the equivalent injected power $S_{eq,i}$ to the bus i not only includes the power $S_{R,i}$ from the renewable generation source directly connected to bus i, but also considers the power $S_{R,j}$ injected from other renewable generation sources and scaled by a weighted coefficient $\frac{Z^*_{RR,ij}}{Z^*_{RR,ii}} \cdot \frac{V_{R,i}}{V_{R,j}}$ to account for the interactions among renewable generation sources. Where $Z_{RR,ij}$ is the electrical distance between the renewable generation source j and bus i; $Z_{RR,ii}$ is the Thevenin equivalent impedance at bus i; $V_{R,i}$ and $V_{R,j}$ represent the bus voltage at bus i and bus j, respectively.

Similar as Figure 2, the equivalent two-bus system for the condition of multiple renewable generation sources can be depicted as below

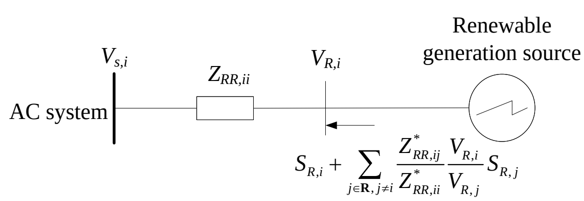

Figure 4. Two-bus equivalent system of AC power system with multiple renewable generation sources

Rearrange the equation (19), consider the critical condition of voltage stability at bus i and follow the steps from (6)-(12), the below relationship can be obtained

$$\frac{|V_{R,i}|\cos\theta_{SR}}{|V_{S,i}|} = \frac{1}{2} = Re\left[\frac{V_{R,i}}{V_{S,i}}\right] \tag{23}$$

Substitute (22) and (23) into (19), the ratio at bus i with respect to the critical condition of voltage stability can be obtained

$$r_i = \frac{|V_{R,i}|^2}{|S_{eq,i}^* \cdot Z_{RR,ii}|} = \frac{|V_{R,i}|^2}{\left|S_{R,i}^* + \sum_{j\in R, j\neq i} \frac{Z_{RR,ij}}{Z_{RR,ii}} \cdot \frac{V_{R,i}^*}{V_{R,j}^*} S_{R,j}^*\right| \cdot |Z_{RR,ii}|} = 1 \tag{24}$$

Equation (24) shows that voltage instability at bus i occurs if the ratio r_i is less than 1 and the bus voltage is stable when the ratio r_i is larger than or equal to 1.

From (16), the commonly used SCR method can quantify the system strength at the POI of RES in terms of the distance to static voltage stability limit under the condition of single RES integration. Moreover, the value of SCR equals to 1 indicates a critical condition of voltage stability at the POI of RES. When the situation of multiple RES integrated into the power system is considered, a new method is developed based on (24) to quantify the system strength at the POI of RES in terms of the distance to static voltage stability limit. Replace the complex power in (24) by the rated capacity of RES to propose the site-dependent SCR (SDSCR) method as below

$$SDSCR_i = \frac{|V_{R,i}|^2}{|P_{d,i} + \sum_{j\in R, j\neq i} w_{ij} \cdot P_{d,j}| \cdot |Z_{RR,ii}|} \tag{25}$$

where

$$w_{ij} = \frac{Z_{RR,ij}}{Z_{RR,ii}} \cdot \left(\frac{V_{R,i}}{V_{R,j}}\right)^* \tag{26}$$

So far, the new method SDSCR has been derived based on the commonly used SCR method with the consideration of interactions among multiple RES. In the next section, the properties of this new method will be introduced in detail.

Section 3.2 Properties of SDSCR Method

This newly proposed SDSCR method has following properties:

The SDSCR method was derived based on commonly used SCR method. Like SCR, SDSCR methods can evaluate the system strength at the POI of RES in terms of the distance to static voltage stability limit. When the value of SDSCR at bus i is much larger than 1, which implies that the voltage at bus i is stable since there is more distance to the voltage stability limit and the bus is regarded as strong. On the contrary, if the value of SDSCR approaches to 1 the strength at bus i becomes weaker since the critical condition of voltage stability is indicated by the SDSCR value of 1. The voltage instability occurs when the value of SDSCR is lower than 1.

The SDSCR method incorporating the effect of interactions among RES through the consideration of real electrical connection among RES. According to the formula of SDSCR method derived in (25), this new method not only take the power $P_{d,i}$ injected from renewable generation source directly connected to bus i into consideration, but also take into account the power $P_{d,j}$ injected from other renewable generation source by a weighted coefficient in (26). The weighted coefficient shows that the impact of injected power $P_{d,j}$ from other renewable generation sources on the system strength at bus i depends on the ratio of electrical distance $\frac{Z_{RR,ij}}{Z_{RR,ii}}$ and the ratio of bus voltage $\frac{V_{R,i}^*}{V_{R,j}^*}$. The impact of renewable generation source at bus j becomes significant if the electrical distance $Z_{RR,ij}$ is close to the Thevenin equivalent impedance $Z_{RR,ii}$ at bus i and the voltages at bus i and bus j are approximately same. So, multiple renewable generation sources will interact with each other and oscillate together like a single huge unit if they are electrically close in a given area.

Like SCR method, the SDSCR method can evaluate the system strength at each individual point of interconnection of renewable generation sources, but with an incorporation of interactions among renewable generation sources. With the condition of multiple RES integration, the SDSCR method can provide more accurate results in the identification of the weakest point in a given region compared with SCR method.

The SDSCR method derived in (25) is a general form of commonly used SCR expressed in (16). When only a single renewable generation source is integrated into the power system, the injected power from other renewable generation sources equal to zero. In this case, the formula of SDSCR method can be simplified to the commonly used one. In other words, SDSCR method can be used to evaluate the system strength at the POI of RES either for single renewable generation source or the power system with multiple renewable generation sources.

Section 3.3 Validation of SDSCR Method

In this section, the efficacy and accuracy of the derived SDSCR method are validated through numerical simulations on the IEEE 39-bus test system. The stability boundary of renewable generation sources is determined at the preliminary step. Then the SDSCR method is compared with commonly used SCR, WSCR and CSCR methods for different operating conditions selected from stability boundary under base case and contingency case. Through the comparison, the SDSCR method can effectively evaluate the system strength for both cases while other three methods overestimate or underestimate the system strength for different operating conditions.

The IEEE 39-bus test system is shown in Figure 5. In this test system, the synchronous generators at bus 31 and bus 32 are replaced by two renewable generation sources. There are following two cases considered for numerical studies.

Base Case: The power system is under the normal operating condition and all the system components are in service.

Contingency Case: The transmission line between bus 6 and bus 7 is out of service due to a contingency.

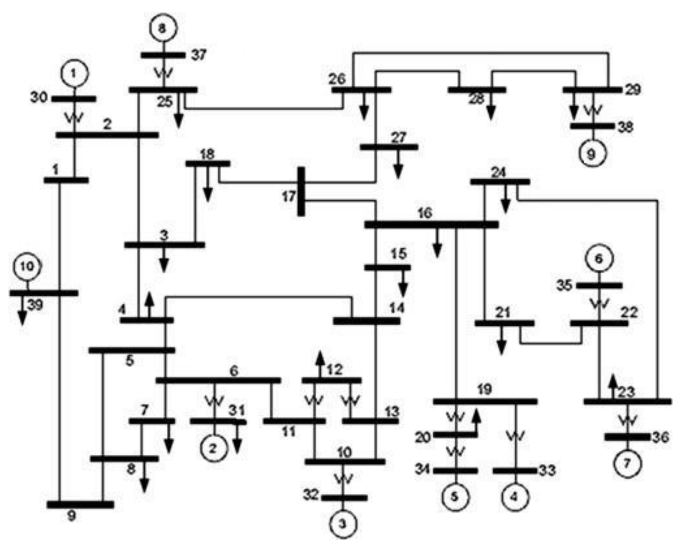

Figure 5. IEEE 39-bus test system

Section 3.3.1 Base Case

The base case is conducted to compare the proposed SDSCR method with SCR, WSCR and CSCR methods when all the system components are in service. Before the numerical simulations on the test system, the stability boundary of renewable generation sources at bus 31 and bus 32 ($P_{d,31}$-$P_{d,32}$) is derived based on the P-V curve analysis. The P-V curve analysis process involves using a series of power flow solutions for increasing transfers of MW and monitoring what happens to system voltages as a result. The initial outputs of two renewable generation sources are set as $P_{d,31}$= 650 MW and $P_{d,32}$= 600 MW respectively. The P-V curve at bus 31 shown in Figure 6 is obtained through a series of power flow solving under the condition of gradually increasing the injected power at bus 31 while maintaining the constant power output at bus 32 until the critical point is reached. The critical point corresponds to the power injection of $P_{d,31}$= 948 MW and $P_{d,32}$= 600 MW, which is a critical operating condition corresponding to a point on the stability boundary shown in Figure 7.

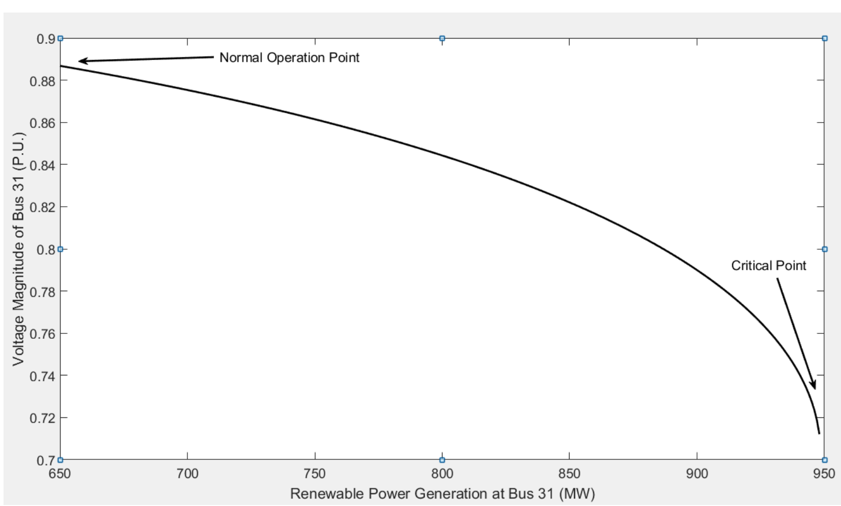

Figure 6. P-V curve at bus 31 in the IEEE 39-bus test system

The P-V curve in Figure 6 shows that the relationship between the bus voltage and transferred power MW is non-linear. This non-linearity is the reason that the faster linear sensitivity methods cannot be used with P-V analysis. At the “knee” of the P-V curve, bus voltage drops rapidly with an increase in power transfer and the power flow solution fails to converge beyond the critical point, which is an indicative of voltage instability. Thus, a satisfactory operating condition for the power system is ensured by a sufficient “power margin”, which refers to a distance to the critical point.

Based on the characteristics of P-V curve, the entire $P_{d,31}$-$P_{d,32}$ stability boundary is derived by the repetition of P-V analysis with respect to different initial outputs of $P_{d,31}$ and $P_{d,32}$. In Figure 7, all the pairs of points ($P_{d,31}$,$P_{d,32}$) inside the stability boundary and outside the boundary correspond to the conditions of system voltage is stable and voltage instability occurs, respectively. As for the pairs of points on the boundary mean that the system is under critical operating conditions.

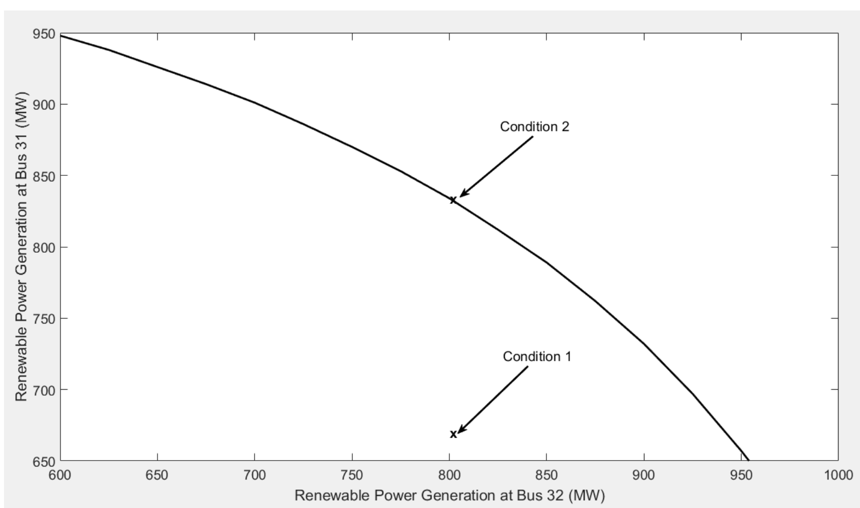

Figure 7. $P_{d,31}$-$P_{d,32}$ stability boundary of renewable generation sources in the IEEE 39-bus system

According to the stability boundary shown in Figure 7, two operating conditions are selected for comparison. The condition 1 is selected inside the stability boundary means that the system is under normal operating condition while the condition 2 is selected on the boundary refers to the critical operating condition. Under these two operating conditions, the four methods are used to evaluate the system strength at the POI of RES. The evaluation results are shown in Table 1 and Table 2. Table 1 presents the voltage magnitudes at bus 31 and bus 32 under two different operating conditions and Table 2 is a comparison between four methods under these two conditions.

Table 1 Voltage magnitudes at buses 31 and 32 under two different conditions

Operating Condition	Power Injection (MW)		Bus Voltage (P.U.)	
	Bus 31	Bus 32	Bus 31	Bus 32
Condition 1	670	800	0.8415	0.8548
Condition 2	834	800	0.7113	0.7534

Table 2 Comparison between SCR, WSCR, CSCR and SDSCR under two different conditions

Operating Condition	Power Injection(MW)		SCR		WSCR		CSCR		SDSCR	
	Bus 31	Bus 32	Bus 31	Bus 32	Bus 31	Bus 32	Bus 31	Bus 32	Bus 31	Bus 32
Condition 1	670	800	2.3902	2.1538	1.1344		2.3023		1.6363	1.6044
Condition 2	834	800	1.4115	1.7204	0.7801		1.7351		1.0575	1.1983

From Table 1, the voltage magnitudes at bus 31 and bus 32 reduce when increasing the power injection at bus 31 while keeping the constant power output at bus 32, which implies that the interaction of RES in the system. The power injection at bus 31 cannot only affect the voltage stability at bus 31 but also lead to a voltage reduction at bus 32. The voltage magnitudes at buses 31 and 32 are 0.8415 p.u. and 0.8548 p.u. under condition 1, which are far from their stability limits 0.7113 p.u. and 0.7534 p.u. under condition 2. From Table 2, the SDSCRs at buses 31 and 32 are 1.6363 and 1.6044 under condition 1, which are much larger than 1 as expected. When the system is under condition 2, the critical values of voltage magnitude at buses 31 and 32 are 0.7113 p.u. and 0.7534 p.u. respectively. The corresponding SDSCRs at these two buses are 1.0575 and 1.1983, which are close to 1 as expected. Moreover, the SDSCR at bus 31 is much closer to 1 compared with bus 32 under condition 2. Since the power is directly injected to the bus 31 and the voltage at bus 32 is only affected by the interaction of RES, so the voltage at bus 31 approaches to its stability limit earlier than bus 32. Thus, the SDSCR method can evaluate the system strength in terms of the distance to the voltage stability limit.

It can be observed from Table 1 and Table 2, the WSCR method underestimates the system strength at the POI of RES. Under condition 1, the voltages at buses 31 and 32 are still far away from their stability limits while the value of WSCR is close to 1, which should be larger than 1 as expected. It is obvious that the value of WSCR is already less than 1 at buses 31 and 32 under condition 2, which indicates the voltage instability occurs in the system, but in fact, the system is under the critical operating condition and the value of WSCR should be close to 1. Thus, the results of WSCR method is conservative and it underestimates the system strength in terms of the distance to the voltage stability limit. Finally, the SCR and CSCR methods overestimate the system strength at the POI of RES. From both tables, the voltages at buses 31 and 32 reach their stability limits under condition 2. It is expected that the both of SCR and CSCR at these two buses are close to 1. However, the values of SCR and CSCR are still much larger than 1 under the critical operating condition, which suggests that the results of SCR and CSCR methods are overly-optimistic and they overestimate the system strength in terms of distance to the voltage stability limit.

Therefore, through a comparison of four methods under two different operating conditions, the efficacy and accuracy of newly proposed SDSCR method are demonstrated for the base case. Next, the contingency case will be conducted with the consideration of the removal of a transmission line in the system and a new stability boundary will be derived for validation of SDSCR method under this case.

Section 3.3.2 Contingency Case

In this case, a new $P_{d,31}$-$P_{d,32}$ stability boundary is derived in case of a transmission line between bus 6 and bus 7 is out of service. In Figure 8, there is a comparison of stability boundaries for the base case and contingency case, the dashed line corresponds to the stability boundary for the base case and the solid line represents the new stability boundary under the contingency case. Clearly, the stability boundary under contingency case is lower than the one under base case. Since the number of the feasible path for the power delivery is reduced and the system becomes more stressed and vulnerable due to the removal of a transmission line in the system. Moreover, the critical point in condition

2 for the base case is now out of the new boundary, which indicates the voltage instability occurs in the system under the contingency case.

Based on the new stability boundary, the efficacy and accuracy of SDSCR method are further validated through system strength evaluation as well as the voltage at buses 31 and 32 with other SCR-Based methods under the contingency case. Similar as the base case, two operating conditions are chosen for comparison, the condition 1 is same as the one in the base case and the condition 3 is a critical operating condition on the new stability boundary. The evaluation results are shown in Table 3 and Table 4.

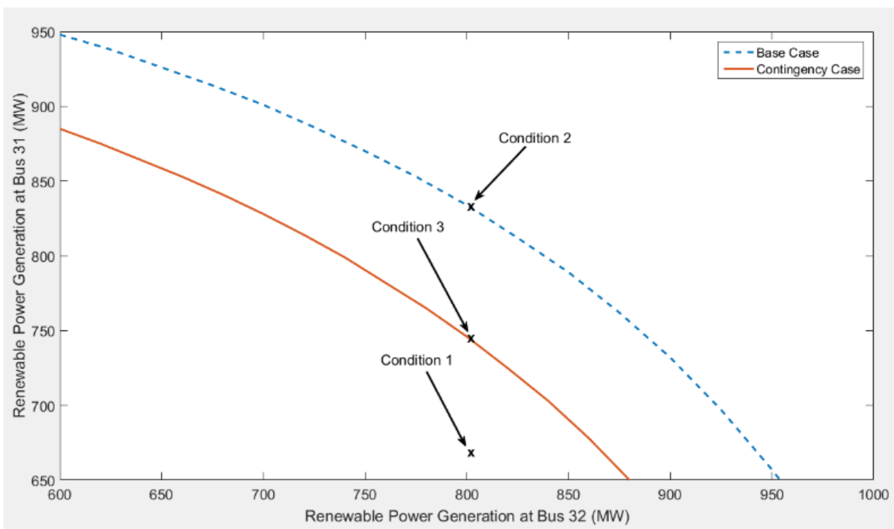

Figure 8. $P_{d,31}$-$P_{d,32}$ stability boundary of renewable generation sources in the IEEE 39-bus system with line 6-7 out of service

Table 3 Voltage magnitudes at buses 31 and 32 under two different conditions

Operating Condition	Power Injection (MW)		Bus Voltage (P.U.)	
	Bus 31	Bus 32	Bus 31	Bus 32
Condition 1	670	800	0.8040	0.8139
Condition 3	746	800	0.7184	0.7464

Table 4 Comparison between SCR, WSCR, CSCR and SDSCR under two different conditions

Operating Condition	Power Injection(MW)		SCR		WSCR		CSCR		SDSCR	
	Bus 31	Bus 32	Bus 31	Bus 32	Bus 31	Bus 32	Bus 31	Bus 32	Bus 31	Bus 32
Condition 1	670	800	2.1421	1.9553	1.0241		2.0786		1.4608	1.4461
Condition 3	746	800	1.5638	1.6542	0.8071		1.7330		1.1188	1.1870

From Table 3 and Table 4, the SDSCR method still effectively evaluate the system strength at the POI of RES in terms of the distance to the voltage stability limit under the contingency case. The values of SDSCR at buses 31 and 32 are still much larger than 1 under condition 1, and at the meantime, the voltage magnitudes at buses 31 and 32 are far from their stability limits under this normal operating condition. While under condition 3, the voltages at buses 31 and 32 approach their stability limit. It is expected that the values of SDSCR at these two buses are close to 1. The expected results can be observed from these two tables.

Similar analytical results can be obtained through a comparison between other SCR-Based methods. The WSCR method underestimates the system strength in terms of the distance to the voltage stability limit. Through observation, the value of WSCR is very close to 1 under condition 1, which should be much larger than 1 as expected. Under condition 3, the value of WSCR is much smaller than 1 implies that the voltage instability occurs, but actually the system is still under the critical operating condition. The SCR and CSCR methods still overestimate the system strength under the contingency case. The values of SCR and CSCR at buses 31 and 32 are still much larger than 1 under condition 3, which should be close to 1 as expected.

Section 3.4 Chapter Summary

In this Chapter, the SDSCR method was derived and proposed based on the properties of commonly used SCR method under the case of multiple RES integration in the power system. Through numerical simulations, the SDSCR method is compared with SCR, WSCR and CSCR method to validate its efficacy and accuracy in system strength evaluation at the POI of RES. The results show that this newly proposed SDSCR method has following advantages: (1) it can quantify the system strength in terms of the distance to the static voltage stability limit; (2) it takes into account the effect of interactions among RES by real electrical connection; (3) it can measure the system strength at each individual point of interconnection of RES; (4) The expression of SDSCR method is a general form of commonly used SCR method, in other words, it is adaptable to both conditions of single RES and multiple RES integration in the power system.

Chapter 4 Investigation of the Impact of Grid Structure on System Strength by SDSCR Method

In this chapter, the newly proposed SDSCR method is used to investigate the impact of grid structure on system strength by two different case studies, especially explore how the transformer and generator's locations affect the system strength at a specific bus. The transformer can be equivalent to an impedance when the grid structure is considered. For the first case study, an extra transformer is added between any two buses in the original system each time and the SDSCR method is employed to evaluate the system strength at a chosen bus to find out the location at which transformer is added will mostly affect the strength at that bus. Similarly, the impact of the generator's location is investigated in the second case study to figure out the location which has the most potential impact on system strength at a chosen bus. Finally, the sensitivity of the grid structure is analyzed and explained.

Section 4.1 Model and Data Description

To investigate the impact of grid structure on system strength, an 8-bus test system is constructed in the PowerWorld software as shown in Figure 9. In this system, bus 2 is set as the slack bus while bus 1 and bus 3 are PV buses, the remaining buses are considered as PQ buses. The bus 4, bus 5 and bus 8 are connected to the load with specified demands. The data of synchronous generators, parameters and thermal limits of transmission lines are summarized in Table 5 and Table 6.

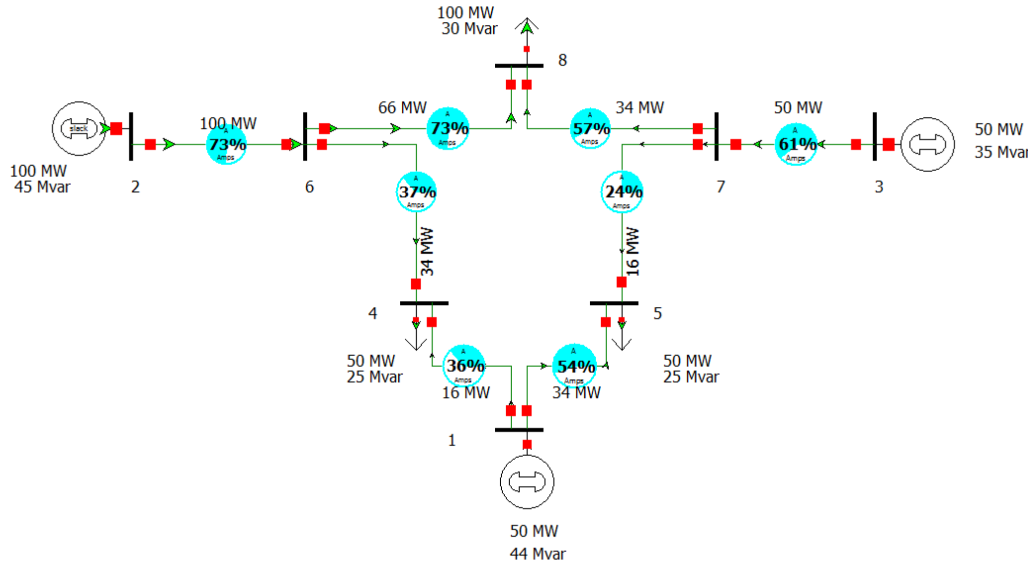

Figure 9. Single-line diagram of the 8-bus test system

Table 5 Generator Data of the 8-bus test system

	Location	Max MW	Min MW	Max MVar	Min MVar
Generator 1	Bus 1	300	0	9900	-9900
Generator 2	Bus 2	200	0	9900	-9900
Generator 3	Bus 3	150	0	9900	-9900

Table 6 Parameters and limit of transmission lines in the 8-bus test system

From Bus	To Bus	Resistance (R)	Reactance (X)	Thermal Limit (MVA)
2	6	0.001	0.1	150
6	8	0.0015	0.25	100
6	4	0.002	0.2	100
4	1	0.001	0.25	75
1	5	0.001	0.25	75
5	7	0.002	0.2	75
7	8	0.0015	0.25	75
7	3	0.001	0.1	100

Section 4.2 Impact of Transformer's Locations on System Strength

The locational impact of the transformer on system strength at a specific bus is investigated in this section. The effect of an additional transformer can be equivalent to a constant impedance when the grid structure is concerned. So, the objective of this case study is to identify the location at which an extra transformer added will significantly affect the strength of a chosen bus.

The 8-bus test system introduced in 4.1 is used for this case study and the system strength at bus 8 is chosen as the study object. Every time, an extra transformer with the constant impedance of *j*0.2 is added to each of the transmission lines in the original system. The impedance of the transformer is in series with the line impedance as shown in Table 6. Then the power flow is calculated after the addition of transformer and the strength at bus 8 is evaluated by the SDSCR method with an assumption of a renewable generation source with the rated capacity of 50MW is connected to bus 8. The base of the system is 100 MVA and simulated results are shown in Table 7 and Table 8. Table 7 is the relevant data of bus 8 before the addition of transformer in the system. Table 8 is the simulated results of system strength at bus 8 evaluated by the SDSCR method after the addition of transformer at all possible locations.

Table 7 Simulation results of system strength at bus 8 before the addition of the transformer

Bus Voltage (p.u.)	Bus Parameters				System Strength
Bus 8	Thevenin R	Thevenin X	$\|Z_{th}\|$	S_{ac}	SDSCR value at Bus 8
0.9098	0.16816	0.27211	0.3122	2.6513	5.303

The magnitude of Thevenin equivalent impedance at bus 8

$$\left|Z_{th,8}\right| = \sqrt{R^2 + X^2} = \sqrt{0.16816^2 + 0.27211^2} = 0.3198$$

The short circuit capacity at bus 8

$$S_{ac} = \frac{V_8^2}{Z_{th,8}} = \frac{0.9098^2}{0.3122} = 2.6513$$

The system strength at bus 8 before the addition of the transformer

$$SDSCR_8 = \frac{S_{ac}}{P_{rated}} = \frac{2.6513}{0.5} = 5.303$$

Table 8 Simulation results of system strength at bus 8 after the addition of the transformer

From Bus	To Bus	Total Line Impedance	Voltage at Bus 8 (P.U.)	$\lvert Z_{th} \rvert$	S_{ac}	SDSCR Value
2	6	0.001+j0.3	0.8717	0.3145	2.4160	4.83
6	8	0.0015+j0.45	0.8817	0.3351	2.3198	4.64
6	4	0.002+j0.4	0.9091	0.3245	2.5468	5.09
4	1	0.001+j0.45	0.9066	0.3189	2.5774	5.15
1	5	0.001+j0.45	0.9053	0.3186	2.5725	5.14
5	7	0.002+j0.4	0.9113	0.3249	2.5558	5.11
7	8	0.0015+j0.45	0.8856	0.3362	2.3328	4.66
7	3	0.001+j0.3	0.8865	0.3189	2.4643	4.93

It can be observed from Table 7 and Table 8, the system strength at bus 8 decreased wherever the transformer is added to the possible locations of the original system. Because the Thevenin equivalent impedance at bus 8 increased due to the additional transformer introduced into the system. Before the addition of transformer, the system strength evaluated by the SDSCR method at bus 8 is 5.303 as shown in Table 7, and SDSCR values decreased to 4.64 and 4.66 when a transformer is added to the transmission line 6-8 and 7-8 respectively. These two locations lead to the largest declines in SDSCR values compared with other locations, which implies that they affect the system strength at bus 8 significantly. Also, these two locations indicate the smallest values of SDSCR when the effect of the additional transformer is concerned.

Through the comparison of the system strength at bus 8 for all possible locations of the additional transformer in the system, it is obvious to see the system strength will be affected mostly when a transformer is added closer to the chosen bus. Since the transformer impedance is directly in series with the line impedance which links to that specific bus. Thus, the Thevenin equivalent impedance at the bus increased remarkably and further lead to a reduction in system strength at the chosen bus.

4.3 Impact of Generator's Locations on System Strength

The objective of this section is to investigate the impact of generator's location on system strength and find out the potential location which has a considerable influence on system strength at a specific bus. Same as 4.2, the 8-bus test system is used and the system strength at bus 8 is selected as the study object. The generator 3 is changed to each of the possible locations in the system to test and compare their impact on the strength at bus 8. Except the bus 1 and bus 2 which already connected to a synchronous generator, there are 5 possible locations for generator 3, they are bus 4, 5, 6 ,7 and 8. Since the generator 3 is removed from the bus 3 and there is no load directly connected to this bus, so the bus 3 is deleted from the original system and the new one is a 7-bus system. Figure 10 is an example of the system with generator 3 connected to bus 7.

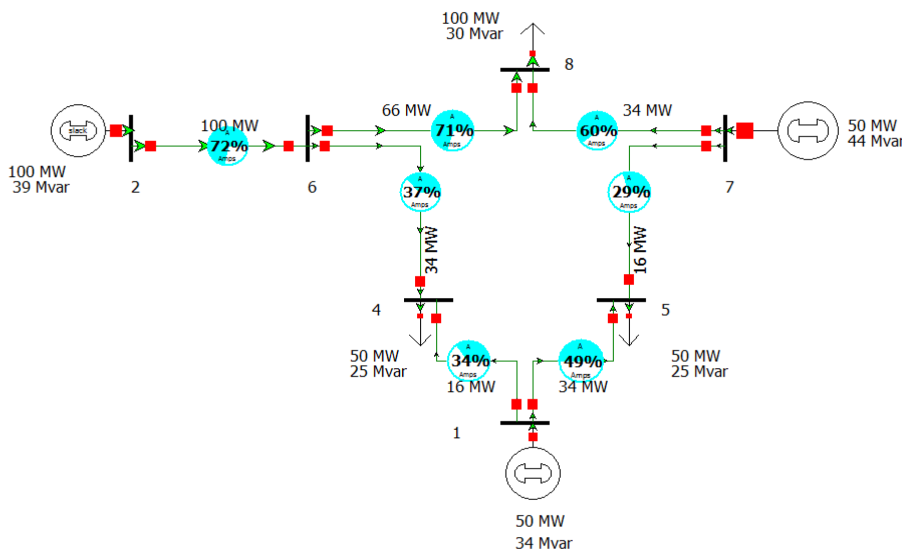

Figure 10. Single line diagram of the 7-bus system with generator 3 connected to bus 7

The procedure for system strength calculation at bus 8 is the same as shown in 4.2 and the simulated results for all possible locations of generator 3 is presented in Table 9.

Table 9 Simulation results of system strength at bus 8 for all possible locations of generator 3

Location of Generator 3	Voltage at Bus 8 (P.U.)	Z_{th}	S_{ac}	SDSCR Value
Bus 4	0.8560	0.3249	2.2550	4.51
Bus 5	0.9021	0.3367	2.4172	4.83
Bus 6	0.8887	0.3198	2.4700	4.94
Bus 7	0.9325	0.3221	2.6994	5.39
Bus 8	1.0000	0.2934	3.4083	6.81

It can be observed from Table 9, the largest SDSCR value at bus 8 is 6.81 under the case of generator 3 is directly connected to bus 8 and the relative minimum SDSCR values occur when the generator 3 is located at bus 4 and bus 5. Compared the simulated results with the system structure shown in Figure 10, it is not difficult to see the system strength at bus 8 is highly dependent on the relative distance of the synchronous generator to the chosen bus. The essential reason for that is the Thevenin equivalent impedance seen at bus 8 reduced if the synchronous generator is closer to it. There are 5 potential locations for generator 3 in this 7-bus test system, bus 4 and bus 5 are relatively far from the bus 8 which show a quite small value of system strength at bus 8 compared with other locations. When the synchronous generator is directly connected to the bus 8, the system strength becomes strong and indicated by a comparatively large SDSCR value.

4.4 Sensitivity of the Grid Structure

The system strength at a specific bus can be affected by the Thevenin equivalent impedance and its relative distance to the synchronous generator. Through the two case studies, some observations are summarized as follow: (1) Introduce an additional transformer into the system will decrease the system strength at a specific bus since the Thevenin equivalent impedance at that bus is increased; (2) The system strength at a bus will be affected more when a transformer is added closer to it; (3) The system strength at a bus is highly dependent on the relative distance to the synchronous generator; (4) The system strength is strong when a synchronous generator directly connected to it.

Chapter 5 Application of SDSCR Method in Transfer Capability Calculation

The electric power system is rapidly growing in complexity and control requirements. To ensure the reliable and economic operation of the system, infrastructure with increasing levels of distributed generation deployment, various entities and subsystems needs a higher level of coordination. Such coordination requires a formal decentralized control and management architecture that creates mechanisms for the planning and operation of these entities [20]. A key function in power system planning and operations is the determination of total transfer capability (TTC), or the maximum amount of power that can be reliably transferred from a set of source points to a set of sink points with the consideration of various imposed security constraints. In recent decades, the increasing penetration of RES has led to some reliability issues due to the variation and uncertainty of these natural resources. The reliability issues will increase the risks of system overloads, equipment damage or the occurrence of blackouts if the TTC of RES is not accurately estimated. Therefore, it is necessary for the system planners and operators to pay more attention to the TTC calculation in terms of integrated RES from a security perspective.

In chapter 3, the efficacy and accuracy of SDSCR method in system strength evaluation at the POI of RES are validated. In this chapter, the impact of integration of geographic dispersed RES on TTC is studied by application of SDSCR method. A procedure of TTC calculation by incorporating SCR-based system strength measurement is designed and implemented at the preliminary step. Then, the accuracy of SDSCR method is further demonstrated in TTC calculation by numerical simulations based on criteria that the lower voltage limit is not compromised under normal operating conditions for base case and contingency case. Finally, a comparative study is conducted to investigate the impact of renewable's locations on TTC under the scenarios of SDSCR method calculation and P-V curve analysis.

Section 5.1 Overview of Transfer Capability

In restructured power markets, the powers producers and customers will share the transmission network and try to maximize their benefits by procuring power from the cheapest energy resources [21]. However, this may result in the violation of line flows, voltage and generation limits, affecting the system security and reliability to some extent. Hence there exists a technical challenge of finding the optimal balance between maximum power transfer and system stability margin. This is important since the transfer capability dominates critical decision making of power system planning and operations. Therefore, the system planners and operators need to accurately evaluate TTC to ensure that system reliability and stability are maintained. Conventionally, TTC is defined as the amount of electric power that can be transferred over the interconnected transmission network in a reliable manner while meeting all of a specific set of defined pre- and post-contingency system conditions [22]. TTC is a time-varying parameter and depends upon various conditions such as the current operating condition, system control capability and the contingencies used for evaluation. Usually, TTC will be constrained by the following factors:

- Thermal limits (line MVA, loading limits)
- Voltage limits (voltage magnitude limits)
- Stability limits (voltage stability limits, transient and dynamic angle stability limits)

The limiting conditions used for TTC calculation can shift among thermal, voltage and stability limits as the network operating conditions change over time. Such variations make the determination of TTC a non-trivial task. Moreover, the real and reactive power limits of the generator should be considered for TTC evaluation as well. Overall, a quick and reliable prediction of TTC is a need of today as it should be open-accessed to all the participants of the power markets.

Nowadays, the penetration of renewable generation sources, primarily wind and solar, continuously increases and is expected to reach 20%−30% in many regional grids in the USA by the year 2020 [23][24]. As the demand for the deployment of distributed renewable energy grows, so does the need for the support of more sophisticated energy management and coordination across the subsystems, a good estimation of TTC in terms of integrated RES becomes more important to the reliable control and operation of the power system. However, the outputs of wind and solar power plants can deviate from their scheduled outputs significantly, it is now critical to evaluate ensembles of load and renewable generation scenarios for revealing the impact of renewable transfer capability limits on the power grid. The TTC with respect to the RES can be defined as the maximum electric power that can be moved or transferred reliably from a group of renewable generation sources to the power grid which are interconnected together. The schematic diagram for the power delivered from the RES to the power grid is shown in Figure 11.

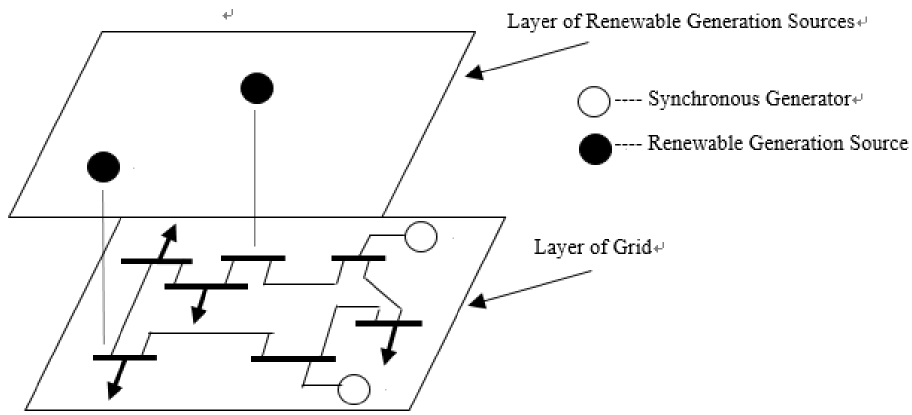

Figure 11. Schematic diagram for the power delivery from renewable generation sources

From Figure 11, the lower layer stands for the topological connection of the power grid and the upper layer represents a group of RES. The focus of the entire chapter is the TTC of the group of RES imposed by the constraints of lower voltage limits and SCR-based system strength measurement. In the next section, a procedure for TTC calculation with respect to the integrated RES will be proposed.

Section 5.2 Procedure for Transfer Capability Calculation

Based on a brief overview of TTC in renewable energy aspect in 5.1, a procedure for TTC calculation by incorporating SCR-based system strength measurement is proposed in this section. The whole procedure for TTC calculation is given in the flow chart as shown in Figure 12. This modified formulation for TTC calculation finds out the maximum electric power that can be delivered from the RES without compromising the threshold values of SCR-based methods.

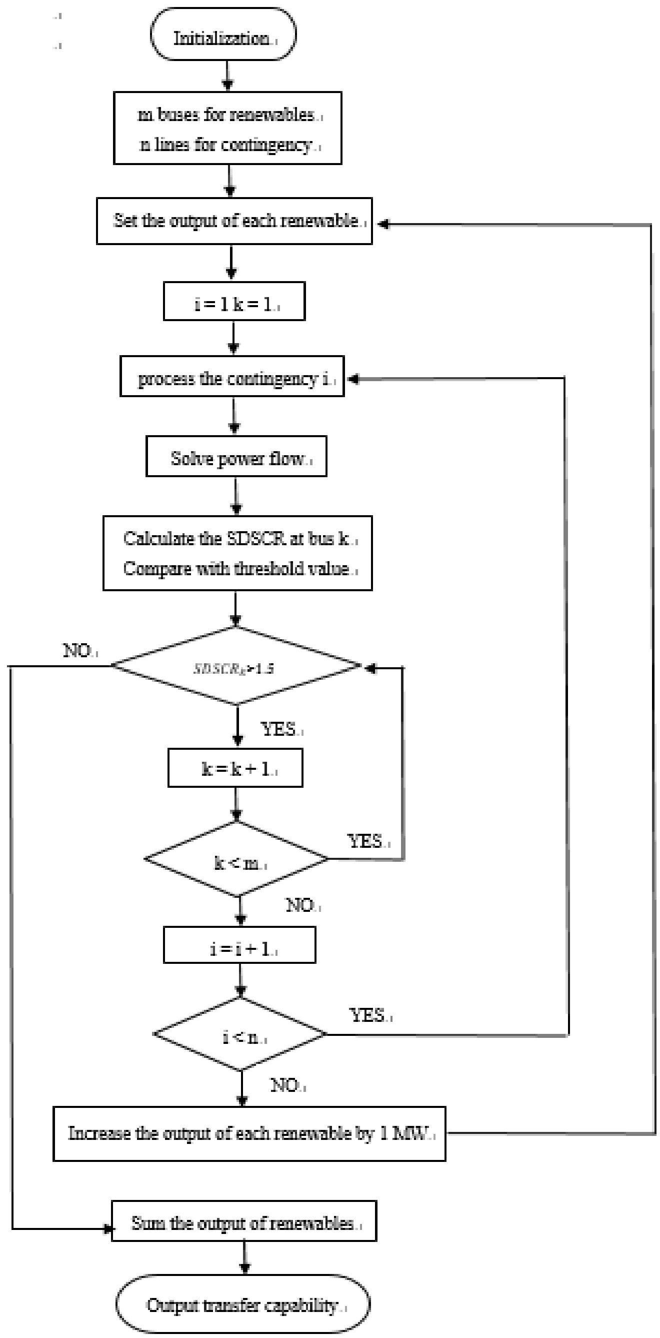

Figure 12. Flow chart for TTC calculation incorporated by SDSCR method

The whole procedure consists of n repetitive experiments until the TTC is obtained in terms of renewable energy injection and it begins with the following indicative preliminaries:

- Designate the buses in the system that connected to the RES (i.e., m buses)
- Set the initial output of each RES (i.e., 30 MW for each RES)
- Define a contingency list includes a set of transmission lines (i.e., n lines)

The first experiment begins with the consideration of first contingency (removal of the first transmission line from the system) in the list, then the power flow is calculated based on the initial setting of renewable's output, that is 30 MW for each RES. The SDSCR values at all points of interconnection of the renewables can be obtained through the equation (25). Last but most important, each calculated SDSCR value should be compared with its threshold. If there exists at least one SDSCR value below its threshold, the whole procedure will be directly terminated due to the violation of the desired system strength and the sum of current outputs of renewables is a transfer capability. If all the SDSCR values with respect to first contingency are above its threshold, then the first experiment continues to be executed for the second contingency. Same as the first one, all the calculated SDSCR values corresponding to the second contingency need to be checked with its threshold. This process repeated until the last contingency in the list is simulated to complete the first experiment. The experiment will be immediately interrupted if at least one of the SDSCR value below the threshold occurs whichever contingencies in the list is simulated.

If all the SDSCR values corresponding to each contingency are above the threshold in the first experiment, which implies that the initial setting of renewable's output can be reliably transferred into the system without compromising the system strength at the POIs of RES and the TTC of these RES is not reached in this experiment. Then the second experiment will be executed with respect to a new setting of renewable's outputs, that is, the output of each RES is increased by 1MW based on their initial outputs. A small step size of 1MW is chosen can effectively reduce the error in this iterative procedure of TTC calculation. The entire process of the second experiment is the same as the first one, and the SDSCR value at each POI of RES will be checked with the threshold for each contingency in the list. If all the SDSCR values for each contingency are above threshold in the second experiment, then the next experiment will be executed. So, such repetitive experiment will continue to execute until at least one SDSCR value below its threshold occurs in experiment n. While in experiment n-1, all the SDSCR values for each contingency are still above the threshold, then the sum of current output for each RES in experiment n-1 is the TTC of these RES in this system.

Section 5.3 Demonstration of SDSCR Method

In this section, the newly proposed SDSCR method will be used to evaluate the TTC and compared the simulated results with other two SCR-based methods on the IEEE 30-bus test system to further validate its accuracy in TTC calculation under base case and contingency case. In chapter 2, the limitations of commonly used SCR method were revealed. Since the SCR method ignores the interactions among RES which will lead to an inaccurate result, it will not be considered for the demonstration of SDSCR method in TTC calculation. In section 5.3.1, a theoretical analysis based on lower voltage limit at the buses that connected to RES is conducted as a criterion for comparison of simulated results. After that, the TTC evaluated by SDSCR method will be compared with the results obtained by WSCR and CSCR methods individually under two cases to validate its accuracy in 5.3.2.

Section 5.3.1 Theoretical Analysis

In this section, a theoretical analysis includes three different situations is proposed for further comparison of simulated TTC results by SCR-based methods. For each situation, two main assumptions are considered, the one is the difference of TTC values obtained by SDSCR method and WSCR/CSCR method. And the other is voltage stability limit, that is, whether the voltage magnitudes at the POIs of RES exceed the lower voltage limit. Typically, a voltage magnitude of 0.9 p.u. is used as an indicator of voltage stability under normal operating conditions. If the magnitude of bus voltage below this value implies the occurrence of instability. In general, to validate the accuracy of SDSCR method in TTC calculation, the TTC value evaluated by SDSCR method should be larger than the one obtained by WSCR/CSCR method, and the voltage magnitudes at the POIs of RES are above 0.9 p.u. in the meantime. Below are the situations with different assumptions.

- Situation 1
    (1) If TTC obtained by SDSCR method is larger than that obtained by CSCR/WSCR method, and voltage magnitudes at the POIs of RES are above 0.9 p.u. for SDSCR method while the voltage magnitudes are also above 0.9 p.u. for CSCR/WSCR method, then the result of SDSCR method is more accurate than CSCR/WSCR method.

    (2) If TTC obtained by SDSCR method is larger than that obtained by CSCR/WSCR method, and voltage magnitudes at the POIs of RES are below 0.9 p.u. for SDSCR method while the voltage magnitudes are above 0.9 p.u. for CSCR/WSCR method,

then the result of CSCR/WSCR method is more accurate than SDSCR method.

(3) If TTC obtained by SDSCR method is larger than that obtained by CSCR/WSCR method, and voltage magnitudes at the POIs of RES are above 0.9 p.u. for SDSCR method while the voltage magnitudes are below 0.9 p.u. for CSCR/WSCR method, then the result of SDSCR method is more accurate than CSCR/WSCR method.

(4) If TTC obtained by SDSCR method is larger than that obtained by CSCR/WSCR method, and voltage magnitudes at the POIs of RES are below 0.9 p.u. for SDSCR method while the voltage magnitudes are also below 0.9 p.u. for CSCR/WSCR method, then neither the result of SDSCR method nor the CSCR/WSCR method are accurate.

- Situation 2

(1) If TTC obtained by SDSCR method is smaller than that obtained by CSCR/WSCR method, and voltage magnitudes at the POIs of RES are above 0.9 p.u. for SDSCR method while the voltage magnitudes are also above 0.9 p.u. for CSCR/WSCR method, then the result of CSCR/WSCR method is more accurate than SDSCR method.

(2) If TTC obtained by SDSCR method is smaller than that obtained by CSCR/WSCR method, and voltage magnitudes at the POIs of RES are above 0.9 p.u. for SDSCR method while the voltage magnitudes are below 0.9 p.u. for CSCR/WSCR method, then the result of SDSCR method is more accurate than CSCR/WSCR method.

(3) If TTC obtained by SDSCR method is smaller than that obtained by

CSCR/WSCR method, and voltage magnitudes at the POIs of RES are below 0.9 p.u. for SDSCR method while the voltage magnitudes are above 0.9 p.u. for CSCR/WSCR method, then the result of CSCR/WSCR method is more accurate than SDSCR method.

(4) If TTC obtained by SDSCR method is smaller than that obtained by CSCR/WSCR method, and voltage magnitudes at the POIs of RES are below 0.9 p.u. for SDSCR method while the voltage magnitudes are also below 0.9 p.u. for CSCR/WSCR method, then neither the result of CSCR/WSCR method nor the SDSCR method are accurate.

- Situation 3

(1) If TTC obtained by SDSCR method is the same as that obtained by CSCR/WSCR method, and the voltage magnitudes at the POIs of RES for all methods are below 0.9 p.u., then neither the result of CSCR/WSCR method nor the SDSCR method are accurate.

(2) If TTC obtained by SDSCR method is the same as that obtained by CSCR/WSCR method, and the voltage magnitudes at the POIs of RES for all methods are above 0.9 p.u., then either the result of CSCR/WSCR method or the SDSCR method are accurate.

Section 5.3.2 Simulation and Comparison

The IEEE 30-bus test system as shown in Figure 13 is used for demonstration of SDSCR method in TTC calculation. In this system, synchronous generators at buses 22 and 23 are replaced by the renewable generation sources with an initial output of 30W each. To ensure the accuracy, the output of each renewable generation sources is increased by 1MW simultaneously until the threshold value is reached. The efficacy and accuracy of SDSCR method are validated by two sets of comparison (i.e., SDSCR and WSCR, SDSCR and CSCR).

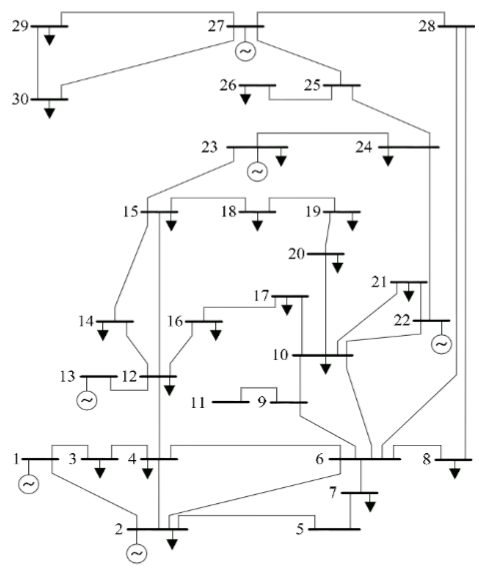

Figure 13. Single-line diagram of the IEEE 30-bus system

The following two assumptions are considered in the numerical simulations:

(1) Like WSCR and CSCR methods, the SDSCR method is also a derivative of commonly used SCR method which exhibits the same properties of the original one. Also, in chapter 3, we verified that the value of SDSCR should be close to 1 under the critical operating condition. When considering the case that the POIs of renewables begin to become unstable, the threshold value of SDSCR method should be larger than 1. To simplify the later comparisons, the value of 1.5 is chosen as a threshold for SDSCR method, which is the same as WSCR and CSCR methods.

(2) Similar to system strength, the voltage magnitude of 0.9 p.u. is set as another physical

constraint to satisfy the security operation of the system. In other words, the procedure for TTC calculation will be immediately terminated if the voltage magnitude at one of the POIs of renewables falls below 0.9.

The following two cases are considered for each set of comparison:

Base Case: The power system is under the normal operating condition and all the system components are in service.

Contingency Case: A set of transmission lines are picked out to constitute a contingency list. Each line in the list will be simulated individually and the predefined contingency list: {Line 15-23, Line 23-24, Line 25-27, Line 27-28, Line 22-24}

Comparison 1: CSCR and SDSCR methods

- Base Case

The accuracy of SDSCR method is validated by comparing it with the CSCR method under the base case with the assumptions and initial setups introduced above. In this case, all the system components are in service and the outputs of renewable generation sources at buses 22 and 23 are increased by 1MW each simulation step until the threshold values for each method are reached. The TTC for each method are investigated and the compared results are shown in Table 10.

Table 10 Simulation results of SDSCR and CSCR methods under Base Case

Method	System Strength		Voltage (p.u.)		Injected Power (MW)		TTC (MW)
	Bus 22	Bus 23	Bus 22	Bus 23	Bus 22	Bus 23	
SDSCR	1.6001	1.505	0.9369	0.9923	90	90	180
CSCR	1.5147	1.5147	0.9359	0.9776	55	55	110

It can be observed from Table 10, the voltage magnitudes at buses 22 and 23 are above 0.9 p.u. when the threshold values of both methods are reached, which satisfy the requirement of system security. Moreover, the TTC obtained by SDSCR and CSCR methods are 180MW and 110MW, respectively. Clearly, the TTC obtained by SDSCR method is larger than CSCR method. According to situation 1 introduced in Section 5.3.1, the CSCR method underestimates the TTC while the results of SDSCR method is more accurate under the base case.

- Contingency Case

Like the base case, the efficacy of SDSCR method is demonstrated and it is compared with the CSCR method under the contingency case. The same assumptions and setups are used and the SDSCR method is evaluated for each contingency defined before. The compared results for each method under contingency case are shown in Table 11.

Table 11 Simulation results of SDSCR and CSCR methods under Contingency Case

Line 15-23 out of service							
Method	System Strength		Voltage (p.u.)		Injected Power (MW)		TTC (MW)
	Bus 22	Bus 23	Bus 22	Bus 23	Bus 22	Bus 23	
SDSCR	1.9488	1.5114	0.9253	1.0092	58	58	116
CSCR	1.5153	1.5153	0.9269	1.0056	53	53	106
Line 23-24 out of service							
Method	System Strength		Voltage (p.u.)		Injected Power (MW)		TTC (MW)
	Bus 22	Bus 23	Bus 22	Bus 23	Bus 22	Bus 23	
SDSCR	1.7824	1.5089	0.9276	1.0117	76	76	152
CSCR	1.5041	1.5041	0.9283	1.0018	55	55	110
Line 25-27 out of service							
Method	System Strength		Voltage (p.u.)		Injected Power (MW)		TTC (MW)
	Bus 22	Bus 23	Bus 22	Bus 23	Bus 22	Bus 23	
SDSCR	1.6183	1.5051	0.9102	0.9622	81	81	162
CSCR	1.5062	1.5062	0.9139	0.9526	54	54	108
Line 27-28 out of service							
Method	System Strength		Voltage (p.u.)		Injected Power (MW)		TTC (MW)
	Bus 22	Bus 23	Bus 22	Bus 23	Bus 22	Bus 23	
SDSCR	1.5981	1.5038	0.9263	0.9853	89	89	178
CSCR	1.5012	1.5012	0.9262	0.9715	55	55	110
Line 22-24 out of service							
Method	System Strength		Voltage (p.u.)		Injected Power (MW)		TTC (MW)
	Bus 22	Bus 23	Bus 22	Bus 23	Bus 22	Bus 23	
SDSCR	1.5693	1.5074	0.9282	1.0013	92	92	184
CSCR	1.5064	1.5064	0.9288	0.9851	55	55	110

It can be observed from Table 11, the SDSCR method can effectively estimate the TTC under the contingency case with given assumptions. Same as the base case, the voltage magnitudes at buses 22 and 23 are still above 0.9 p.u. when the threshold values are reached. Also, the TTC calculated by SDSCR method is larger than the CSCR method for all the contingencies. Based on theoretical analysis, the SDSCR method gives a more accurate result for TTC estimation compared with CSCR method. So far, the newly proposed SDSCR method has been demonstrated for TTC estimation and it is better than CSCR method under base case and contingency case.

Comparison 2: WSCR and SDSCR methods

- Base Case

In this case, the SDSCR method is compared with WSCR method in terms of all the system components are in service. The same assumptions and procedure are applied, and Table 12 shows the compared results for each method under the base case.

Table 12 Simulation results of SDSCR and WSCR methods under Base Case

Method	System Strength		Voltage (p.u.)		Injected Power (MW)		TTC (MW)
	Bus 22	Bus 23	Bus 22	Bus 23	Bus 22	Bus 23	
SDSCR	1.6001	1.505	0.9369	0.9923	90	90	180
WSCR	1.5052	1.5052	0.9373	0.9862	73	73	146

It can be observed from Table 12, the SDSCR method can better estimate the TTC compared with the WSCR method. Since the voltage magnitudes at buses 22 and 23 are above 0.9 p.u., the measured TTC values determine the accuracy of each method. Without compromising the system security, the TTC obtained by SDSCR method is larger than the WSCR method. According to situation 1 introduced previously, the

SDSCR method can accurately evaluate the TTC while the result calculated by WSCR method is conservative.

- Contingency Case

The same contingency list is used to validate the efficacy of SDSCR method under the contingency case and the accuracy of the new method is demonstrated through a comparison with WSCR method. The compared results for each method under this case is shown in Table 13.

Table 13 Simulation results of SDSCR and WSCR methods under Contingency Case

Line 15-23 out of service							
Method	System Strength		Voltage (p.u.)		Injected Power (MW)		TTC (MW)
	Bus 22	Bus 23	Bus 22	Bus 23	Bus 22	Bus 23	
SDSCR	1.9488	1.5114	0.9253	1.0092	58	58	116
WSCR	1.5058	1.5058	0.9263	1.0071	55	55	110
Line 23-24 out of service							
Method	System Strength		Voltage (p.u.)		Injected Power (MW)		TTC (MW)
	Bus 22	Bus 23	Bus 22	Bus 23	Bus 22	Bus 23	
SDSCR	1.7824	1.5089	0.9276	1.0117	76	76	152
WSCR	1.5102	1.5102	0.9284	1.0047	60	60	120
Line 25-27 out of service							
Method	System Strength		Voltage (p.u.)		Injected Power (MW)		TTC (MW)
	Bus 22	Bus 23	Bus 22	Bus 23	Bus 22	Bus 23	
SDSCR	1.6183	1.5051	0.9102	0.9622	81	81	162
WSCR	1.5002	1.5002	0.9128	0.959	68	68	136
Line 27-28 out of service							
Method	System Strength		Voltage (p.u.)		Injected Power (MW)		TTC (MW)
	Bus 22	Bus 23	Bus 22	Bus 23	Bus 22	Bus 23	
SDSCR	1.5981	1.5038	0.9263	0.9853	89	89	178
WSCR	1.5038	1.5038	0.927	0.9794	72	72	144
Line 22-24 out of service							
Method	System Strength		Voltage (p.u.)		Injected Power (MW)		TTC (MW)
	Bus 22	Bus 23	Bus 22	Bus 23	Bus 22	Bus 23	
SDSCR	1.5693	1.5074	0.9282	1.0013	92	92	184
WSCR	1.5085	1.5085	0.9292	0.99	64	64	128

The same results as that in the base case can be observed from Table 13. The TTC value measured by the SDSCR method is always larger than that obtained by WSCR method for each contingency. It is not difficult to draw the conclusion that our SDSCR method is effective for TTC estimation and is more accurate than the WSCR method. Combined with the simulation results in Comparison 1, the efficacy and accuracy of SDSCR method are sufficiently demonstrated and it shows the advantage for TTC estimation compared with other SCR-based methods.

Section 5.4 Impact of Renewable's Locations

In the last section, the efficacy and accuracy of newly proposed SDSCR method were validated through comparisons with WSCR and CSCR methods individually. In this section, the SDSCR method is used to investigate the impact of renewable's locations on TTC and a comparative study is conducted to validate the consistency of the results obtained by our new method and P-V curve analysis.

Section 5.4.1 Transfer Capability Calculation by SDSCR method

To further investigate the location impact on TTC, buses 5, 6, 9 and 28 are selected as the potential sites for installation of renewable energy sources. Each time, two of the sites will be selected and a 30MW renewable is connected to each selected bus.

Similar to the previous procedure, the threshold value of the SDSCR method is chosen as 1.5 for the security operation. And the output of each renewable energy source is increased by 1MW simultaneously until one of the buses reaches its voltage threshold. There are 6 possible combinations of the potential locations and the TTC for each combination is shown in Table 14.

Table 14 Simulation results of TTC for each combination of buses by SDSCR method

	Bus 5 and Bus 6	Bus 5 and Bus 9	Bus 5 and Bus 28
TTC (MW)	206	220	210
	Bus 6 and Bus 9	Bus 6 and Bus 28	Bus 9 and Bus 28
TTC (MW)	236	228	240

This is an extended application of the SDSCR method in TTC application with the consideration of location impact. The aim of this case study is to identify the potential locations for renewable installations with maximum TTC in terms of physical constraints. The reasons of different TTC for each site combination could be attributed to the grid structure, transmission line capacity and the distances between each site. To further explore the location impact on TTC for a set of renewable sites, the TTC will be calculated by the P-V curve in the next section to verify the consistency of the results in this case study.

Section 5.4.2 Transfer Capability Calculation by P-V Curve

In this section, the TTC for each potential combination is calculated by the P-V curve. Unlike SDSCR method from the system strength perspective, the constraint for this case study is the bus voltage at the POI of renewables, which is chosen as 0.9 p.u. for security purpose. Follow the same procedure in section 5.4.1, the output of each renewable is increased gradually until the threshold value of the bus voltage is reached. The simulated results are shown in Table 15 along with the results obtained by the SDSCR method to verify the consistency of different perspectives.

Table 15 Simulation results of TTC for each combination of buses by P-V curve (0.9 p.u.)

	Bus Number	Bus Voltage (p.u.)	Injected Power (MW)	TTC by P-V Curve (MW)	TTC by SDSCR (MW)
Combination 1	Bus 5	0.9875	295	590	206
	Bus 6	0.9004	295		
Combination 2	Bus 5	0.9715	309	618	210
	Bus 28	0.9002	309		
Combination 3	Bus 5	0.9865	317	634	220
	Bus 9	0.9005	317		

Combination 4	Bus 6	0.9005	361	722	228
	Bus 28	0.9244	361		
Combination 5	Bus 6	0.9415	370	740	236
	Bus 9	0.9000	370		
Combination 6	Bus 9	0.9004	379	758	240
	Bus 28	0.9533	379		

Table 15 shows the simulation results of TTC for each combination by the P-V curve and the SDSCR method in ascending order. It is obvious that the results of these two case studies show the consistency. In other word, combination 1 has the smallest value of TTC obtained by the P-V curve, also this value is the smallest by the SDSCR method. Such correspondence can be found for other 5 combinations. To further verify such correspondence, another experiment is done when the threshold value of the bus voltage is chosen as 0.95 p.u. the results are shown in Table 16.

Table 16 Simulation results of TTC for each combination of buses by P-V curve (0.95 p.u.)

	Bus Number	Bus Voltage (p.u.)	Injected Power (MW)	TTC by P-V Curve (MW)	TTC by SDSCR (MW)
Combination 1	Bus 5	1.0091	189	378	206
	Bus 6	0.9502	189		
Combination 2	Bus 5	1.0007	224	448	210
	Bus 28	0.9501	224		
Combination 3	Bus 5	1.0081	225	450	220
	Bus 9	0.9501	225		
Combination 4	Bus 6	0.9500	258	516	228
	Bus 28	0.9707	258		
Combination 5	Bus 6	0.9658	277	554	236
	Bus 9	0.9501	277		
Combination 6	Bus 9	0.9500	283	566	240
	Bus 28	0.9793	283		

The same observation can be found in this table, the TTC obtained by P-V curve exhibits the consistency with the results of SDSCR method. Even though these two methods come from the different perspectives, the setting of an appropriate threshold value can effectively limit the injection of energy from the renewable resources to avoid security issues. In the meantime, the results of these two methods show the consistency suggests both of them are valuable for TTC estimation.

Section 5.5 Chapter Summary

In this chapter, the verified SDSCR method is applied to transfer capability calculation with the penetration of renewable energy sources. Based on the knowledge of transfer capability, a procedure of TTC calculation is designed and implemented. Then the TTC is evaluated by incorporating SDSCR-based system strength measurement for different constraints. Once the efficacy and accuracy of SDSCR for TTC calculation were demonstrated, the impact of renewable's location is investigated, and a comparative study was conducted. The results of SDSCR method and the P-V curve analysis for TTC calculation show the consistency, which suggests both of the methods are qualifiable for the TTC estimation.

Chapter 6 Comparative Study for Identification of the Weakest Area by Cascading Line Outages and SDSCR Method

In this chapter, the weakest area in the IEEE 30-bus test system will be identified by the SDSCR method and cascading line outages from two different perspectives. The way that the SDSCR method examines the weakest area is based on the system strength evaluation, especially the grid structure is the dominant factor for the ultimate results. While the cascading line outages originate from the reliability perspective, except the connectivity of the nodes, the identified results of such method are highly dependent on the limits of the transmission lines. To investigate the relationships of identified weakest areas from two different perspectives using different measures, a comparative study is designed and conducted.

Section 6.1 Overview of Cascading Line Outages

Blackouts in power grids typically result from cascading failures. With the development of power systems in size and complexity, including the growth of smart grids, blackouts due to cascading line outages become more frequently. Cascading line outages in power systems is a process, in which an initial disturbance or component outage increases the stress on the remaining system components, and then a series of critical components are subsequently tripped as a consequence of widespread blackouts. Large electric power transmission systems occasionally have cascading failures will affect up to tens of millions of people [25].

The reasons for cascading failures can be attributed to the loss of generating units, breaker failures, common tower and common right-of-way circuit outages, etc. They can be also caused by a combination of system conditions and external events, which are not necessarily associated with just one transmission path, substation, or generator [26]. Due to the chain reaction and devastating impact of cascading failures, many researchers were attracted to investigate the blackout failure mechanisms with the consideration of cascading overloads and power system reliability.

Section 6.2 Modeling of Cascading Line Outages

The initial ideal for modeling blackout dynamics in power transmission networks was proposed by I. Dobson in [27], it consists of two different time scales, the slow timescale which describes the relationship between load demand and network improvement, another one is fast dynamics of cascading overloads and outages [28]. In this section, only the fast dynamics are considered, and a model is proposed to implement the procedure of cascading line outages based on an initial ideal.

At the beginning of the procedure, each line in the system is simulated to be tripped individually according to their index. Based on the different choice of initial line outage, investigating how the cascading failure is propagated in the system. The line outage is modeled by increasing the line reactance to infinity so that there is no power flow on that line. Once the initial line is determined, the simulation of cascading begin, and the flow chart is shown below:

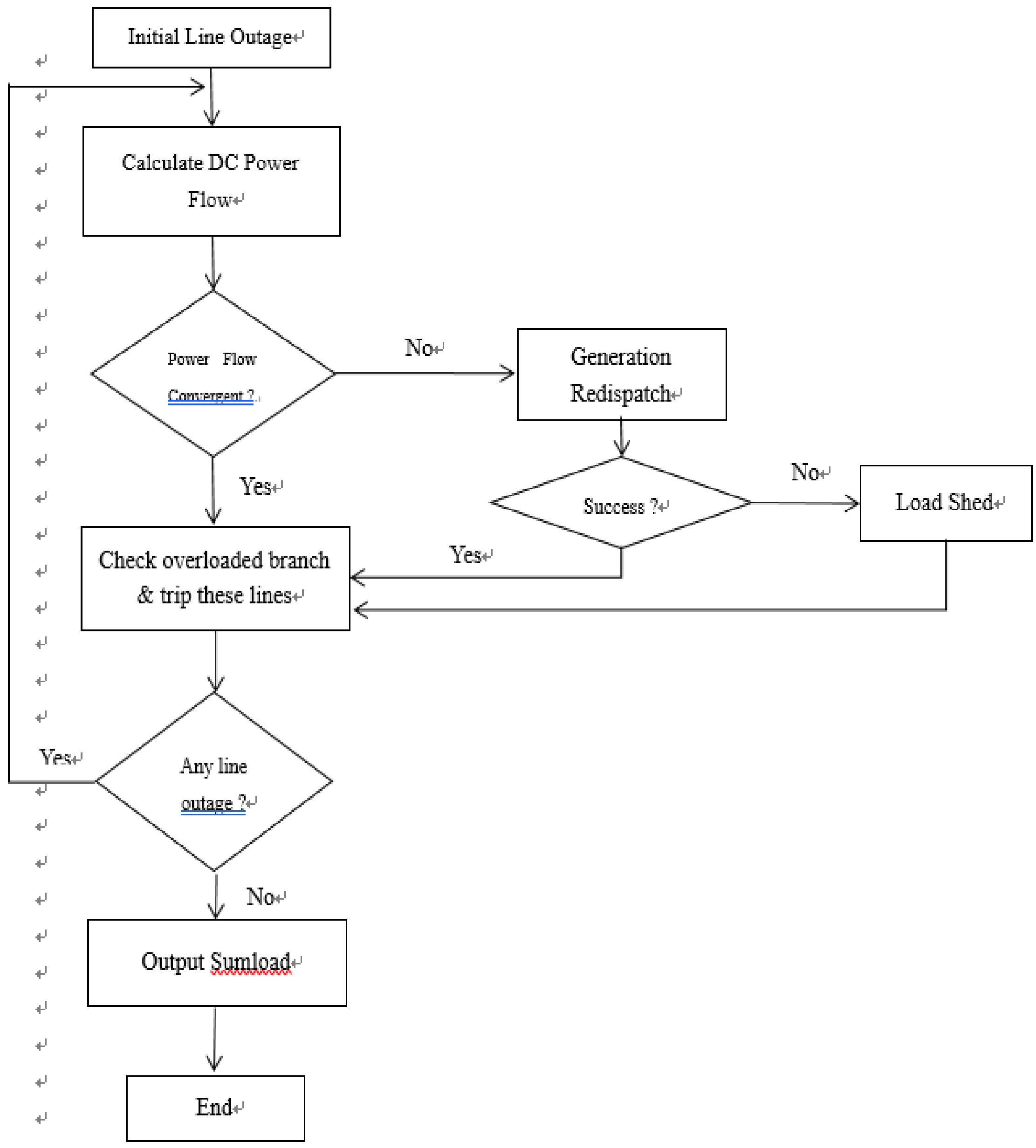

Figure 14. Flow chart of cascading line outages

The complete procedure can be summarized as three main steps performed in a sequence: DC power flow calculation, Generation redispatch and Load shedding. The detailed steps are explained below:

(1) If any lines outage, the B matrix is recalculated as well as DC power flows according to the formula: $P = B\theta$, where P is the vector of real power injections at all the

buses except the reference bus and θ is the vector of voltage angles for each bus.

(2) Check the convergence of DC power flow. If it is, then directly check overloaded lines in this simulated cascade and trip them. These tripped lines will be considered in the next cascade. Otherwise, goes to step (3).

(3) Since the DC power flow was not convergent, generation redispatch is considered as the second choice, which means that the real power output of each generator will be adjusted to satisfy the load demand. If redispatch method works, then check and trip the overloaded lines as (2), if not, goes to step (4).

(4) If redispatch process failed, the only way to ensure the security and reliability of the system is load shed, which regarded as the worst choice.

(5) Please note that overloaded lines should be checked and tripped in steps (2), (3) or (4). The cascade of branch outages continues in this manner until no further lines outage, then the whole simulation ended.

Section 6.3 Weakest Area Identification by Cascading Line Outages

In this section, the IEEE 30-bus test system is used to identify the weakest area based on the cascading model proposed in section 6.2. Unlike the normal way to trip the lines in the system, each node is removed individually as well as all the lines directly connected to that node for weakest area identification. The weakest area is identified according to the amount of loads in service after cascading line outages process. And the results of cascading scenario will be compared with the one of system strength evaluation in section 6.5.

As shown in Figure 13, the 30-bus test system is presented by a single-line diagram. The initial load demand is 189.2 MW for this system, the bus 1 is slack bus while buses 2, 13, 22, 23, 27 are indicated as the PV bus. To identify the weakest area in this system, each node is removed from the system individually according to their index except those initially connected to the generators. The tripped line index and total load shedding for each removal node are shown in Table 17.

Table 17 Simulated results of cascading line outages for the IEEE 30-bus test system

Node	Initial line outage	Consequential line outage	Load Shedding (MW)
3	1-3, 3-4	21-22, 15-23, 22-24, 23-24, 25-27, 27-28	109.76
4	2-4, 3-4, 4-6, 4-12		7.6
5	2-5, 5-7		0
6	2-6, 4-6, 6-7, 6-8, 6-9, 6-10, 6-28	23-24, 25-27, 27-28	62.44
7	5-7, 6-7	15-23, 21-22, 22-24, 23-24, 25-27, 27-28	107.09
8	6-8, 8-28	15-23, 21-22, 22-24, 23-24, 25-27, 27-28	85.4
9	6-9, 9-10, 9-11	15-23, 21-22, 22-24, 23-24, 25-27, 27-28	85.4
10	6-10, 9-10, 10-17, 10-20, 10-21, 10-22	15-23, 27-28	40.49
11	9-11		0
12	4-12, 12-13, 12-14, 12-15, 12-16	15-23, 18-19, 21-22, 22-24, 23-24	127.43
14	12-14, 14-15		6.2
15	12-15, 14-15, 15-18, 15-23	21-22, 22-24, 23-24, 25-27, 27-28	74.53
16	12-16, 16-17	4-12, 15-18, 23-24	13.76
17	10-17, 16-17	4-12	9
18	15-18, 18-19	4-12, 23-24, 12-16, 16-17, 15-23	19.77
19	18-19, 19-20	4-12	9.5
20	10-20, 19-20	15-23, 21-22, 23-24	2.2
21	10-21, 21-22	4-12, 15-23, 10-22, 23-24, 27-28	41.3
24	22-24, 23-24, 24-25	4-12, 15-23	8.7
25	24-25, 25-26, 25-27	27-28	3.5
26	25-26	15-23, 21-22, 22-24, 23-24	3.5
28	6-28, 8-28, 27-28	4-12, 21-22, 15-23, 25-27	99.26
29	27-29, 29-30	15-23, 21-22, 22-24, 23-24, 25-27, 27-28	14.6
30	27-30, 29-30	15-23, 25-27, 27-28, 21-22, 23-24	10.6

The second column of the table indicates the lines directly connected the corresponding nodes and they are tripped before the cascading line outage process. The consequential line outages stand for the lines to be tripped due to the overloading of the following cascades. Finally, the total load shedding is calculated as a cumulated result of the cascading process for each case of the node. It can be observed from the table, the total load shedding is 0 when the nodes 5 and 11 are individually removed from the entire system, which suggests these two nodes are "strong" enough, the generation can be supplied to the load side and satisfy the initial demand without them and corresponding lines. Conversely, there will be consequently 127.43 MW load shedding when the node 12 is removed from the system, which refers to approximately 70% load cannot be reliably supplied, so this node is indicated as a "weak" node for cascading process. Similarly, the nodes 3, 7 and 28 will lead to more than half of load shedding following the cascading line outages, they are also considered as the "weak" nodes. There are some distances between these identified "weak" nodes since this system is small and only used for research purpose. While in the practical situation, a large system has nodes up to thousands or ten thousand, the constraints between nodes can be more distinct. When following this cascading line outage process, it is not hard to find out the weakest area with a clutch of adjacent nodes and impose necessary measures and monitoring to ensure the entire system under the safe and reliable condition.

Section 6.4 Weakest Area Identification by System Strength Evaluation

To conduct a comparative study and investigate the relationships between results obtained from two different perspectives. The weakest area of the IEEE 30-bus test system identified by the SDSCR method from the system strength aspect is done in this section. As introduced in chapter 3, the newly proposed SDSCR method has been demonstrated its efficacy for system strength evaluation with the consideration of interactions among renewable energy sources. While, in this case the system strength is assessed one by one with a connection of 30MW renewable energy source at each bus individually except those initially connected to the generators. The evaluated results of system strength for the 30-bus system are shown in Table 18.

Table 18 Results of system strength evaluation for the IEEE 30-bus test system

Node	3	4	5	6	7	8	9	10
SDSCR	6.2863	6.377	5.8627	6.6622	5.3679	5.0688	6.2889	6.3037
Node	11	12	14	15	16	17	18	19
SDSCR	4.8661	5.7779	5.0509	5.6844	5.5547	5.7148	5.1988	5.0565
Node	20	21	24	25	26	28	29	30
SDSCR	5.387	5.6559	5.5336	5.041	3.3126	6.3698	3.652	3.3539

It can be observed from the above table, most of the nodes have an SDSCR value around 5 to 6 with respect to the connection of 30 MW renewable energy source, which indicates they are “strong” enough for the penetration of renewables. While the SDSCR values at nodes 26, 29 and 30 are a little more than 3, which is relatively “weak” compared with other nodes. In the meantime, compare the results in Table 15 with the single-line diagram of the 30-bus system shown in Figure 13, it is clear that these “weak” nodes are all in the upper left corner of the system. So, this area should be noted and take enough measures before integration of renewable energy sources.

Section 6.5 Comparison and Analysis

So far, the weakest area has been identified through two scenarios from two different perspectives in sections 6.3 and 6.4, it is necessary to investigate the relationships between the results for these two scenarios and give a reasonable explanation.

From the scenario of cascading line outages, the simulation results show that the weakest points in the 30-bus test system are located at buses 3, 7, 12 and 28. However, the weakest points identified from the scenario of system strength evaluation are buses 26, 29 and 30. On the face of things, the results of two scenarios do not show the consistency due to the consideration of different perspectives. Since cascading line outages is more relative to the limits of the transmission lines while the system strength is highly dependent on the grid structure. But still some key factors can be explored from a deeper insight and give a rational explanation to the results of this comparative study.

For the scenario of cascading line outages, the criticality ranking of nodes could be a dominant factor for the ultimate results. This factor refers to two different aspects, the one can be explained as the number of lines directly connected to a specific node. The more lines connected to a node, the more importance it is. Another aspect comes from the total capacity of the lines directly connected to a node, similar to the first aspect, larger capacity indicates a high ranking of the corresponding node. If a node satisfies either or both of the above aspects and it is removed for the simulation of cascading line outages, the total load shedding could be tremendous. As for the scenario of system strength evaluation, no doubt that the connectivity of the nodes is the key factor since it will definitely affect the power flows through the whole grid when the renewable energy sources are integrated into some specified points. Finally, the size of the system cannot be neglected. The 30-bus test system is small, and the simulation results may not be obvious for the comparative study. When considering the large system with thousands of nodes, the simulation results will be more accurate and close to expectations.

Conclusions

1. Integration of the renewable energy sources to the weaker portions of the power system could lead to the issues related to voltage stability and quality. Enough system strength is required to support voltage and maintain the normal operation. Recently, Short Circuit Ratio has been used to evaluate the system strength at the point of interconnection of renewables. However, this method does not consider the interactions among renewables, the result is overly-optimistic. The Weighted SCR and Composite SCR has been proposed to account for such interactions, but they ignore the real electrical connections among renewables, so the results could be misleading.
2. The new proposed Site-Dependent SCR method can effectively overcome the defeats of these SCR-based methods. Compared with them, the SDSCR method has following advantages: (1) it can quantify the system strength in terms of the distance to the static voltage stability limit; (2) it takes into account the effect of interactions among RES by real electrical connection; (3) it can measure the system strength at each individual point of interconnection of RES; (4) The expression of SDSCR method is a general form of commonly used SCR method, in other words, it is adaptable to both conditions of single RES and multiple RES integration in the power system.
3. After the demonstration of SDSCR method for system strength evaluation, it is used to investigate the impact of grid structure on system strength and following conclusions are obtained: (1) Introduce an additional transformer into the system will decrease the system strength at a specific bus since the Thevenin equivalent impedance at that bus is increased; (2) The system strength at a bus will be affected

more when a transformer is added closer to it; (3) The system strength at a bus is highly dependent on the relative distance to the synchronous generator; (4) The system strength is strong when a synchronous generator directly connected to it.

4. The newly proposed SDSCR method can be used for transfer capability calculation, and the obtained results of this method are more accurate than other SCR-based methods with the consideration of voltage constraints. Also, the SDSCR method can be extended to investigate the location impact of renewables. The calculated transfer capability by SDSCR method shows the consistency with the one obtained by the P-V curve analysis.
5. The SDSCR method can be used to identify the weakest area in a power grid with penetration of renewables. The results of the SDSCR method do not show the consistency with the one simulated by the cascading line outages due to the consideration of different perspectives. Cascading line outages is more relative to the limits of the transmission lines while the system strength is highly dependent on the grid structure.

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