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Dipartimento di Ingegneria Industriale DII

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Allocation of Synchronous Condenser for optimizing overcurrent capabilities in inverter base resources integrated grid

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Abstract

The rapid integration of Inverter-Based Resources (IBR) into power grids, driven by the rise in renewable energy sources, poses significant challenges to grid stability due to the inherent limitations of inertia, overcurrent capabilities and reactive power control in these resources. This research proposes the integration of IBRs and Synchronous Condensers into a Grid Strengthening Setup (GSS), where the Synchronous Condenser regulates terminal voltage, providing essential inertia and overcurrent capabilities, while IBRs regulate frequency. The study focuses on the power system network of the Faroe Islands, a small and isolated grid heavily dependent on diesel generators. As the region aims to shift towards renewable energy, Synchronous Condensers become a crucial consideration to mitigate the loss of inertia and reactive power control resulting from decommissioning diesel power plants. The project entails identifying the weakest Point of Interconnection (POI) and strategically allocating Synchronous Condensers in the Faroe Islands' power network. The methodology involves short circuit analysis using MATLAB, calculating Short Circuit Ratios (SCR), and introducing Weighted Short Circuit Ratios (WSCR) to gauge grid strength. Allocation decisions will be based on comparing SCR and WSCR at different positions in the power system. This research, positioned at the intersection of advancements in grid-forming technologies and the decentralization of power systems, renews the significance of Synchronous Condensers in addressing challenges posed by IBR integration. The outcomes aim to enhance the stability and strength of the isolated power system network in the Faroe Islands, facilitating a seamless transition from diesel-fired generators to renewable energy sources.

Contents

Nomenclature

Abbreviations

IBR	Inverter based resources
SC	Synchronous condenser
SCR	Short circuit ratio
GSS	Grid strengthening setup
$WSCR$	Weighted short circuit ratio
POI	Point of interconnection
$p.u$	Per unit
SVC	Static var compensator
$STATCOM$	Static synchronous compensator
PCC	Point of common coupling
SCC	Short circuit capacity
MVA	Mega volt ampere
P_r	Rated active power
U_k	Nominal bus voltage
Z_k	Thevenin equivalent impedance
AC	Alternating current
DC	Direct current
MW	Mega watt
U_t	Terminal voltage
U_s	Equivalent system voltage
i_{inj}	Injected current
WPP	Wind power plant
PMU	Phasor measurement unit
kV	Kilo volt
kA	Kilo ampere
VU	Full converter system
U_{ers}	Pre-fault voltage
$\mathrm{I''}_{\mathrm{koVU}}$	Thevenin short-circuit current
$\mathrm{I''}_{\mathrm{kVU}}$	Short-circuit current contribution by IBR
YKK	Nodal admittance matrix

YYsub	Sparce matrix nxn
YYG	Augmented admittance matrix
$3ph$	Three phase supply
YT	Terminal admittance matrix
WF	Wind farm
KKT	Node incidence matrix
DG	Deisel generator
$BESS$	Battery energy storage system
HP	Hydro-power
WP	Wind Park
FSC	Full scale converter
$DFIG$	Doubly fed induction generator
WT	Wind turbine

List of Figures

List of Tables

1. Introduction

The escalating integration of Inverter-Based Resources (IBR), fueled by the proliferation of renewable energy sources, has introduced formidable challenges to grid stability and reliability. The inherent limitations of IBRs, characterized by a lack of inertia and reactive power control, undermine the grid's ability to cope with disturbances, particularly during fault conditions and substantial load fluctuations.

The commercial power electronics inverters currently in use fall short, providing overcurrent capabilities of less than 2 p.u. In contrast the conventional synchronous generator can provide up to 5 p.u. of the rated current during the fault condition.[1] To tackle this challenge, various technologies, including Static Var Compensators (SVCs), Static Synchronous Compensators (STATCOMs), and Synchronous Condensers (SCs), have been considered. However, conventional dynamic reactive support devices, such as SVCs and STATCOMs are failed to provide the necessary fault level and inertia support.[2]

A synchronous condenser, also known as a synchronous compensator or synchronous capacitor, is a specialized type of rotating electrical machine used in power systems for reactive power control and voltage regulation. It operates on the same principle as a synchronous motor but lacks any mechanical load attached to its shaft. Instead, its primary function is to generate or absorb reactive power as needed to support the voltage and stability of the power system. So as compare to SVCs and STATCOMS, SCs which operates on the principle of delivering lagging vars in an overexcited state emerge as a superior solution, offering both smooth voltage regulation and enhanced inertia during grid faults.

The allocation of SCs will be based on the evaluation of SCR. The SCR values can be calculated by utilizing the load flow studies and performing short circuit analysis. In literature, several articles analyze and assess SCR as an indicator of grid strength.

The short circuit analysis of the power system containing IBRs is different and complex as compare to the grid containing conventional grid. For this reason, no analytical equations are available and thus, experts need to rely on empirical or semi-empirical correlations that have been proposed by researchers in the past.

The purpose of this work is to analyze optimal allocation of SCs and evaluate the consequential changes in grid strength, as measured by the SCR value, following the installation of an SC. The experimentation phase of this research was conducted at the "Institute for Electrical Energy Systems" within the esteemed precincts of the "Leibniz University Hannover." The developed MATLAB algorithm, a pivotal component of this research, was rigorously tested in conjunction with the ongoing project in the Faroe Islands. Furthermore, the algorithm underwent extensive verification through testing on additional test grids to ensure robustness and validity. This approach not only enhances the reliability of our findings but also extends the potential applicability of the proposed SC allocation strategy to diverse power system scenarios.

2. Theoretical basis

The short-circuit level at a bus reflects the maximum current during a fault, determined by contributions from system resources on nominal voltages. It primarily gauges system resilience to faults and is used in metrics like the Short Circuit Ratio (SCR) as an indicator of relative system strength. Power system strength influences stability assessments, with a strong system correlating with reduced risks like voltage instability and adverse control interactions. For any AC/DC converter, SCR is the short-circuit level (in MVA) at the point of common coupling (PCC) or POI divided by the installed DC system rating (in MW)[3]. Systems are often labeled weak or strong based on SCR, where a high SCR denotes a strong system, and vice versa. In converter-dominated power systems, limited thermal capacity of semiconductor devices results in lower short-circuit current contributions, leading to inherently lower SCR values compared to synchronous-generator-based systems. This traditionally categorizes converter-dominated systems as weak, suggesting a higher likelihood of instability [4].

In an AC system, the impedance reflects system strength, and the SCR offers a means to gauge this impedance relative to the installed DC system rating [3]. This concept is applicable to synchronous-generator-based systems, where generators act as voltage sources behind impedance during faults[5]. Recent dynamic studies involving converters have also embraced this principle. For instance, the study in [6] explores the minimum short-circuit ratio necessary for stable AC/DC systems, utilizing SCR to derive a system representation through an equivalent AC system impedance.

2.1 Definition and Principles of Short Circuit Ratio (SCR)

To assess system strength, the SCR is defined as the ratio of the three-phase short-circuit capacity (SCC) in MVA at the POI to the active power rating of the DC system (P_r) in MW. This definition is expressed as:

$$SCR = \frac{SCC}{P_r} \tag{2.1}$$

This measure is commonly used as a preliminary indicator to assess the anticipated level of interactions between converters and the rest of the power system[7]. The short-circuit capacity at the POI is represented as:

$$SCC = \frac{U_k^2}{Z_k} \tag{2.2}$$

Where U_k is the nominal bus voltage, and Z_k is the Thevenin equivalent of AC system impedance as seen from the POI.

Imagine a location within an AC system having SCC in MVA, where a DC link with a rated power P_r in MW is about to be linked. The equivalent impedance, expressed in per unit, specifically when the rated DC power is selected as the base power, can then be computed as:

$$Z_k = \frac{P_r}{SCC} \tag{2.3}$$

Thus, the system equivalent can be drawn as shown in Figure 2.1, indicating that the system's impedance can be estimated by having information about the short-circuit capacity.

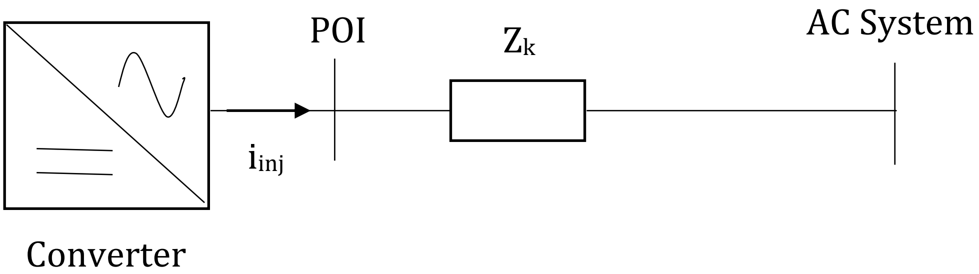


Figure 2.1: Equivalent circuit of AC system as seen from the POI.

Moreover, by utilizing the system equivalent in Figure 2.1, the anticipated level of interactions between the converter and the AC system can be illustrated as follows:

Let U_t and U_s represent the voltage at the POI and the AC system equivalent bus, respectively. The POI voltage is then expressed as

$$U_t = U_s + i_{inj}.Z_k \tag{2.4}$$

Assuming the voltage at the AC system bus (U_s) is rigid, if there is a change in the injected current (Δi_{inj}), the alteration in the POI voltage is given by

$$\Delta U_t = \Delta i_{inj}.Z_k \tag{2.5}$$

This implies that a larger system impedance (Z_k) leads to a more abrupt change in the POI voltage, indicating a more pronounced interaction and, consequently, a weaker system[4]

As per [8] , a point within an AC system is deemed weak if its Short Circuit Ratio (SCR) falls between 2 and 3. If the SCR is below 2, the AC system is labeled as very weak. Conversely, if the SCR exceeds 3, the system is considered strong. This threshold is visually depicted in Figure 2.2.

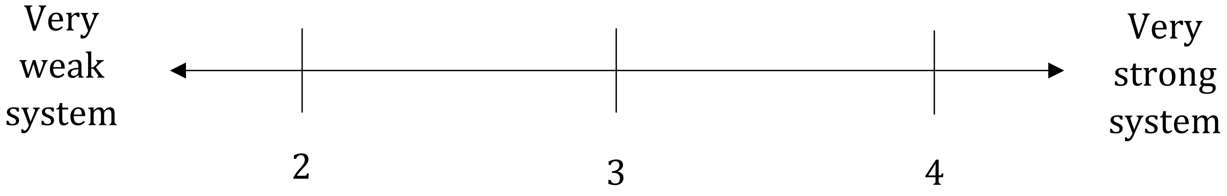


Figure 2.2: SCR threshold depiction

2.2 Concept of Weighted Short Circuit Ratio (WSCR)

The strength of a power system, measured by the SCR, has a direct impact on how stable and oscillatory IBRs behave within that system. While traditional SCR calculations are commonly used to assess system strength, it's crucial to consider how IBRs interact. [9].

The impact of diminished system strength on IBRs performance is exemplified by a recent incident within the Electric Reliability Council of Texas (ERCOT) [10]. A wind power plant (WPP) is linked to the ERCOT grid via two 69kV transmission lines, performing well under standard conditions with SCR of approximately 4. However, if one 69kV line is offline, the SCR drops to 2 or below. During an incident where one 69kV line was taken out of service, the WPP encountered poorly damped or undamped voltage oscillations, recorded by Phasor Measurement Units (PMUs) at the POI. Investigation revealed that the oscillations resulted from the aggressive voltage control of the WPP, unsuitable for a weakened grid. The wind generator voltage controller experienced a low short circuit level and high voltage control gain, leading to the observed oscillations. In weak grid conditions, the closed-loop voltage control exhibited a faster response compared to normal conditions with a higher SCR. Simulation of the event, employing a detailed dynamic model of the WPP, demonstrated effective damping of oscillations with a higher SCR, illustrated in the purple curve in Figure 2.3. Reducing the voltage controller gain also improved the oscillatory response, depicted in the green curve in Figure 2.3.

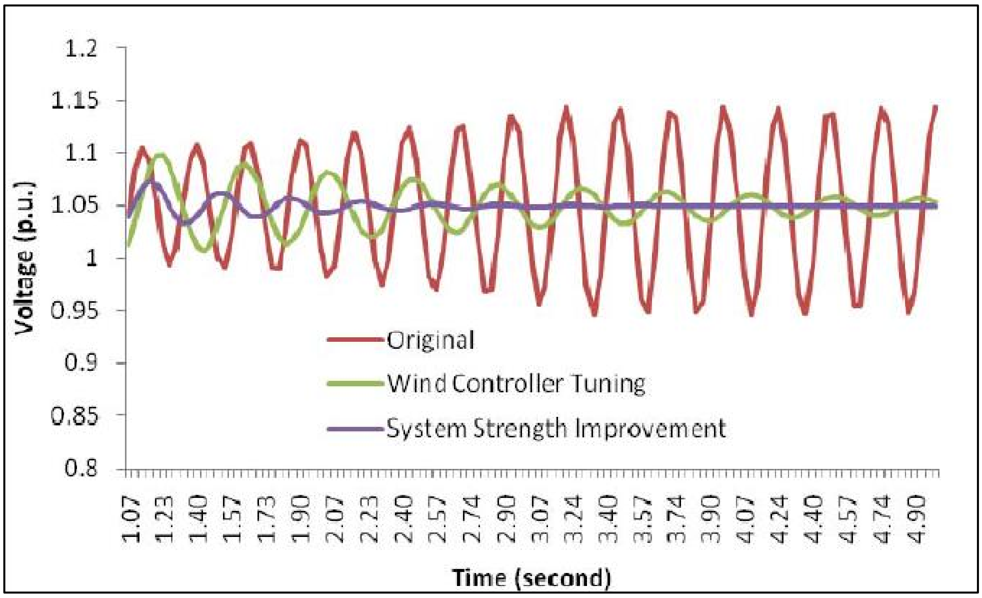


Figure 2.3: Voltage response at WPP's POI. (Red: original, Green: wind voltage control tuning, Purple: High SCR)

If IBRs collectively oscillate, the traditional SCR might give an overly optimistic view of the system's strength. To address this, the proposed Weighted Short Circuit Ratio (WSCR) provides a more nuanced view, considering the impact of interactions between IBRs [9]. This refined approach offers a better representation of system strength. The broader perspective, coupled with a step-by-step methodology for determining optimal synchronous condenser ratings and locations, provides a useful framework to enhance the stability and performance of various Inverter-Based Resources in power systems.

To consider the impact of interactions among IBRs and provide a more accurate estimation of system strength, a more suitable metric is the Weighted Short Circuit Ratio (WSCR) is defined as follows:

$$WSCR = \frac{SCC_{weighted}}{\sum_{i}^{N} \mathrm{P_{ri}}} \tag{2.6}$$

$$= \frac{(\sum_i^N SCC_i * P_r)/\sum_i^N \mathrm{P_{ri}}}{\sum_i^N \mathrm{P_{ri}}}$$

$$= \frac{\sum_i^N SCC_i * P_{ri}}{(\sum_i^N \mathrm{P_{ri}})^2} \tag{2.7}$$

Where SCC_i is the short circuit capacity at bus before the connection of IBR i and P_{ri} is the MW rating of the IBR i to be connected. N is the number of IBRs fully interacting with each other and i is the IBR index.

The method for calculating WSCR proposed here operates under the assumption of complete interactions between IBRs. This assumption is akin to considering that all IBRs are interconnected at a single POI. The SCR obtained through this approach provides a more cautious estimate of the system strength. In actual power systems, it's common for there to be some electrical distance between different POIs, and as a result, wind plants may not fully interact with each other [9, p. 2].

For further clarification about the concept of WSCR, a small sample system comprising four wind plants is considered. In this subsystem, the four wind plants are connected to the main system through weak links, and there is negligible electrical distance between POIs. The sizes of the wind plants and the corresponding SCR values, calculated using formula (2.1), are detailed in Table 2.1.

Wind plant	Wind Capacity (MW)	Short Circuit Capacity (MVA)	SCR
A	1200	6500	5.42
B	1000	8000	8.00
C	800	8500	10.63
D	2000	7000	3.5

Table 2.1: Wind Plant sizes and SCR values assuming no interaction

Considering full interaction, the actual SCR is:

$$WSCR = \frac{1200 * 6500 + 1000 * 8000 + 800 * 8500 + 2000 * 7000}{(1200 + 1000 + 800 + 2000)^2}$$

$$WSCR = 1.464$$

The calculation above reveals a noteworthy observation: while the SCRs at each individual POI exceed 3, which would typically indicate a connection to a strong system, the WSCR for the equivalent POI is merely 1.464. This discrepancy indicates that when these wind plants interact with each other, the actual system strength is considerably weaker than when each wind plant oscillates independently [9].

2.3 Limitation of SCR

The issues with using SCR calculations for assessing system strength arise because we rely on the short-circuit capacity at the POI to estimate the entire system's impedance. In traditional power systems, short-circuit contributions mainly come from synchronous generators. These generators act like voltage sources during faults, and the short-circuit level reflects the system's impedance well. That's why SCR is a good indicator—impedance shows how sensitive the system's voltage is to changes in current.

However, converters, like those used in renewable energy systems, behave differently during short circuits. They are seen more as current sources, continuing to inject current regardless of faults. The values for short-circuit currents in converters depend on control settings, operating conditions, and protection plans. These values don't really tell us much about the actual impedance of converters and the system. Additionally, short-circuit contributions from converters are usually saturated and lower than those from traditional synchronous generators because of the limited capacity of the semiconductor devices used in converters [4].

3 Analytical Framework and Computational Development

The determination of SCR and further WSCR necessitates the undertaking of steady-state short circuit studies, a crucial step in understanding the short circuit currents and capacities at the POI.

The objective of this chapter is to develop a comprehensive formulation for steady-state short circuit analysis tailored for IBRs-dominated power systems. The focus lies on the calculation of short circuit currents and short circuit capacities at all POIs within the system. Subsequently, these fundamental concepts will be harnessed to construct a MATLAB algorithm designed to assess system strength by computing SCR and WSCR.

This chapter will provide a detailed, step-by-step breakdown of the MATLAB program's construction, ensuring transparency and facilitating a thorough understanding of the algorithm's intricacies. The culmination of this effort will involve the practical implementation of the algorithm on an actual power grid. To facilitate this implementation, data will be sourced from the Load Flow analysis of the power system, ensuring a realistic and applicable validation of the formulated concepts in a real-world setting.

Based on the results derived from the formulated steady-state short circuit analysis and the subsequent MATLAB algorithm, the next phase involves the optimal allocation of Synchronous Condensers (SC). This strategic placement aims to enhance overcurrent capabilities and system strength. The optimal allocation process will involve deploying SCs at POIs within the power system. Following the implementation of SCs, the change in system strength will be meticulously assessed and compared against the baseline conditions. This comparative analysis will provide valuable insights into the efficacy of the SC allocation strategy, offering a quantitative measure of the improvement achieved in the overall system strength. The outcomes of this phase contribute to refining and optimizing the integration of SCs within the IBR-dominated power system.

3.1 Steady State Short Circuit Analysis of IBR Dominated Power System

When dealing with power systems comprising only conventional synchronous generators, the short circuit analysis is relatively straightforward and follows conventional methodologies. However, the analysis becomes more complex when IBRs are integrated into the system. Unlike conventional generators, IBRs introduce nonlinear fault current characteristics, compelling the adoption of a more empirical approach. This adjusted methodology takes into account the unique contributions of inverter fault currents by employing equivalent generator impedance calculations. Additionally, consideration is given to inverter output limits, typically falling within the range of 1.1 to 1.3 p.u. This tailored approach is essential for accurately capturing the fault current dynamics introduced by IBRs and ensures that SCR and WSCR calculations appropriately reflect the system's characteristics in the presence of these non-conventional power sources.

Theoretical approach suggested in the formulary given by the “Institut für Elektrische Energiesysteme (IFES, Hannover)” to carry short circuit analysis is based on the Superposition Principle of Electrical networks.

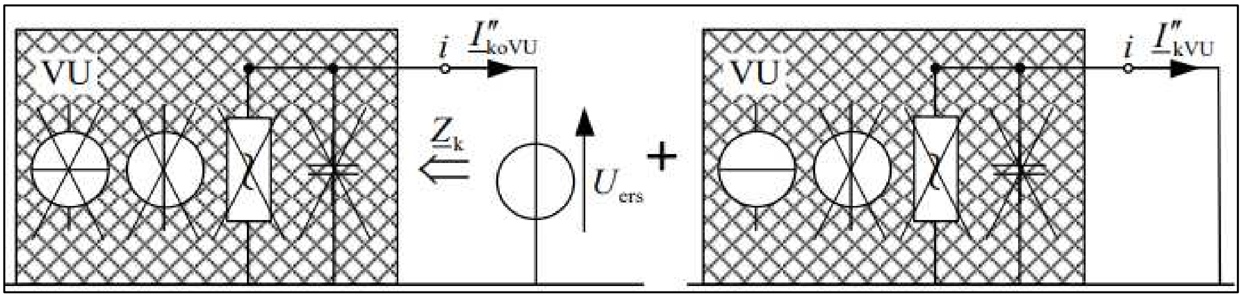


Figure 3.1: Short circuit current calculation for converter system

Full inverter systems (VU) in Figure 3.1 refer to power generation setups linked to the grid through full inverters. In simulations, we model them as ideal current sources. To figure out how much short-circuit current they contribute, we use a rule called the current divider. We then estimate this contribution by adding the actual amounts of their current to the initial short-circuit alternating current[11]. This approach helps us understand

and calculate the impact of full inverter systems on the overall short-circuit conditions in the system.
In Figure 3.1, the initial total short-circuit current can be determined by adding together two current contributions. One comes from the conventional system, represented by the Thevenin equivalent, and the other stems from treating the full inverter system as a current source.

The total short circuit current can be expressed as:

$$I"_{kmax} = I"_{koVU} + I"_{kVU}$$

$$= \frac{U_{ers}}{Z_k} + \frac{1}{Z_k}\sum_{j=1}^{n}(z_{ij} * I_{qVUj}) \tag{3.1}$$

Here, U_{ers} represents the pre-fault voltage, and Z_k is the Thevenin impedance. This combination results in the Thevenin short-circuit current, denoted as I''_{koVU}, which is a contribution from the conventional system. Additionally, z_{ij} and I_{qVUj} represent the impedance and current values provided by the converter systems when treated as a current source, resulting the short circuit current contribution I''_{kVU} from the converter system.

The theoretical framework outlined earlier has been translated into a MATLAB program designed for large power system networks with multiple converter systems. In this research, we applied this approach to compute short-circuit currents, utilizing voltage and impedance matrices extracted from Load Flow studies. The calculated short-circuit current serves as a crucial parameter in determining the Short Circuit Capacity at the POIs. This capacity estimation is instrumental in gauging the grid strength required for the optimal integration of SCs. By understanding and quantifying the short-circuit capacity, we can make informed decisions regarding the strategic placement and integration of SCs to enhance overall grid stability and performance.

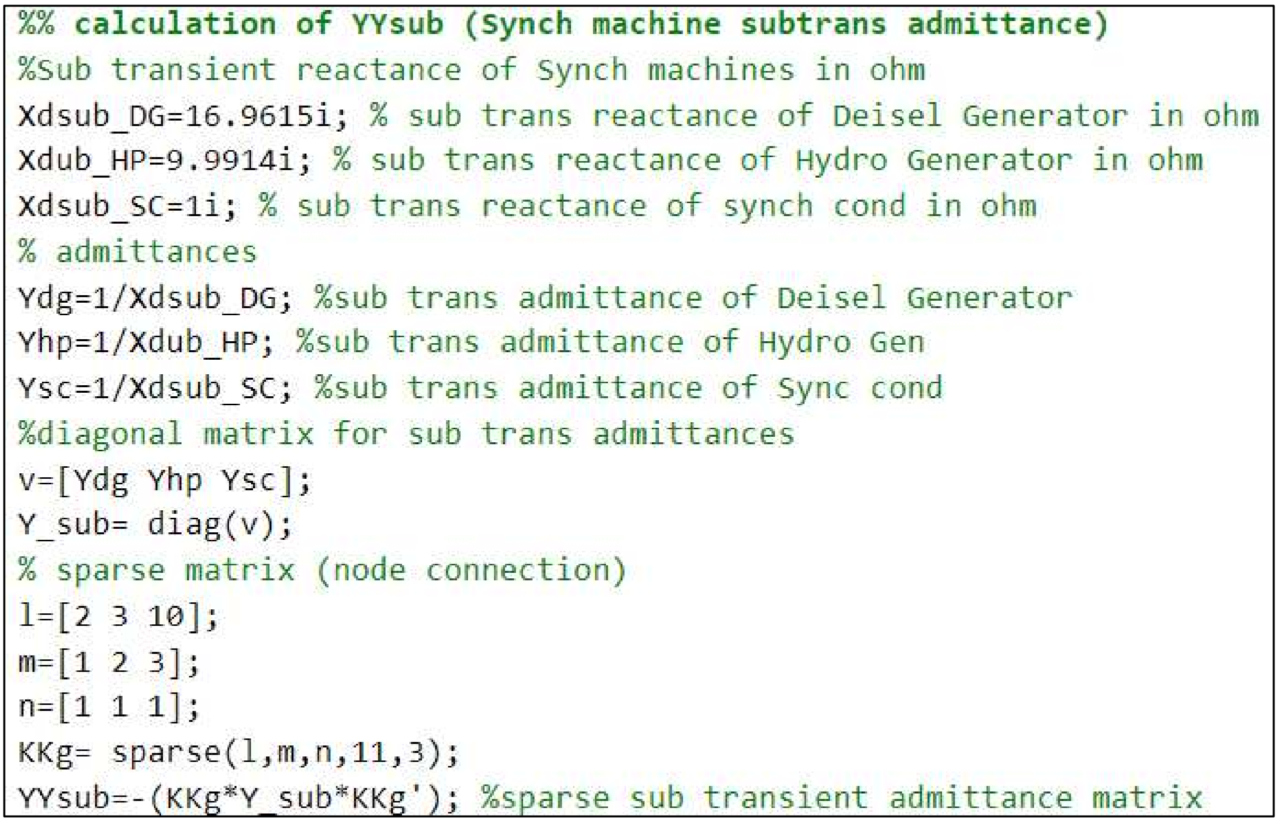
3.2 MATLAB algorithm development

The MATLAB code has been meticulously crafted to offer adaptability for application to diverse power systems, accommodating a variable number of buses and IBRs. The step-by-step elucidation of the code's construction will be contextualized using values and abbreviations derived from the Suduroy, Faroe Island grid data. This specific selection allows for a comprehensive and realistic exploration of the algorithm's intricacies within a unique power system framework. Notably, the grid data, generously shared by the grid operators, has been harnessed from load flow studies, forming a foundational dataset crucial for the progression of this research. By anchoring the code's development in the Suduroy, Faroe Island grid particulars, this approach ensures not only the versatility of the algorithm but also its applicability to real-world scenarios, enhancing the credibility and relevance of the research outcomes.

3.2.1 Updating the Nodal Admittance Matrix [YKK] for Short Circuit Analysis

Upon successful loading of the grid data into the MATLAB workspace, derived from load flow study parameters, the subsequent step involves extracting the Nodal Admittance Matrix [YKK]. This matrix serves as a fundamental element for calculating short-circuit currents at each bus within the power system. Notably, in this computation, the inclusion of the sub-transient reactance for all synchronous machines becomes imperative. The incorporation of sub-transient reactance values in the YKK ensures a comprehensive and accurate representation of the system's dynamic behaviour, particularly in the context of short-circuit current calculations. This meticulous consideration of sub-transient reactance underscores the precision and realism embedded in the algorithm's approach, aligning with the complexities of power system dynamics.

To incorporate the sub-transient reactance, pertinent values are sourced from the respective machine datasheets. These values are subsequently transformed into admittances. The ensuing step involves the creation of a nxn sparse matrix [YYsub], where 'n' denotes the number of buses in the power system. Within this matrix, the sub-transient admittances are strategically positioned as diagonal elements.



```
%% calculation of YYsub (Synch machine subtrans admittance)
%Sub transient reactance of Synch machines in ohm
Xdsub_DG=16.9615i; % sub trans reactance of Deisel Generator in ohm
Xdub_HP=9.9914i; % sub trans reactance of Hydro Generator in ohm
Xdsub_SC=1i; % sub trans reactance of synch cond in ohm
% admittances
Ydg=1/Xdsub_DG; %sub trans admittance of Deisel Generator
Yhp=1/Xdub_HP; %sub trans admittance of Hydro Gen
Ysc=1/Xdsub_SC; %sub trans admittance of Sync cond
%diagonal matrix for sub trans admittances
v=[Ydg Yhp Ysc];
Y_sub= diag(v);
% sparse matrix (node connection)
l=[2 3 10];
m=[1 2 3];
n=[1 1 1];
KKg= sparse(l,m,n,11,3);
YYsub=-(KKg*Y_sub*KKg'); %sparse sub transient admittance matrix
```

Figure 3.2: MATLAB code- creating sparse sub-transient admittance matrix [YYsub]

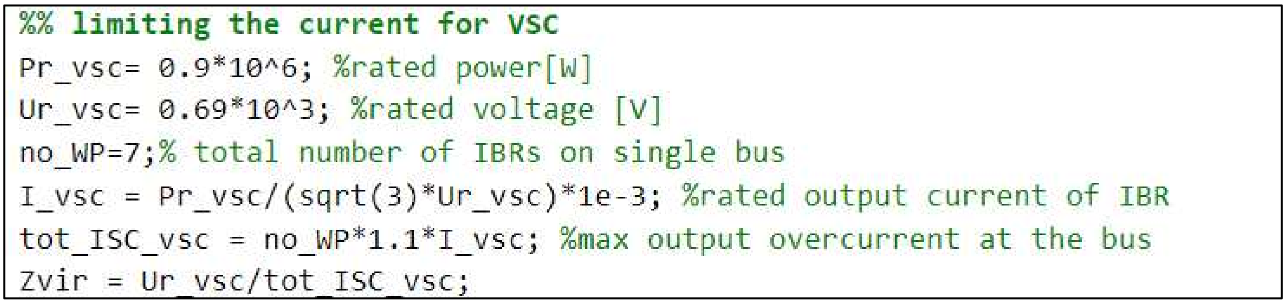
The YKK is then updated to form a new augmented admittance matrix YYG by adding the YYsub to it. This augmented matrix encapsulates the dynamic behaviour introduced by the sub-transient reactance values of synchronous machines. In essence, YYG stands as a comprehensive representation that accounts for the nuanced response of synchronous machines during fault analysis, providing a more accurate depiction of the power system's behaviour under fault conditions.

```
%% updating the admittance matrix
YYG=Leistungsfluss.YKK+YYsub; %updated admittance matrix
```

Figure 3.3: MATLAB code- updated admittance matrix [YYG]

3.2.2 Limiting Current Output of IBRs

In accordance with [1], it has been identified that IBRs exhibit a shortfall in their overcurrent capabilities when confronted with a short circuit fault. To address this intrinsic limitation, a crucial consideration in fault analysis involves imposing a restriction on the maximum short circuit current. In the realm of research and established formulas, a prevalent practice is to constrain the fault current within the range of 1.1 to 1.3 times the rated current [11].



```
%% limiting the current for VSC
Pr_vsc= 0.9*10^6; %rated power[W]
Ur_vsc= 0.69*10^3; %rated voltage [V]
no_WP=7;% total number of IBRs on single bus
I_vsc = Pr_vsc/(sqrt(3)*Ur_vsc)*1e-3; %rated output current of IBR
tot_ISC_vsc = no_WP*1.1*I_vsc; %max output overcurrent at the bus
Zvir = Ur_vsc/tot_ISC_vsc;
```

Figure 3.4: MATLAB code- Limiting maximum overcurrent output of IBR

In Figure 3.4, 1.1 limiting factor for the short circuit current is considered.

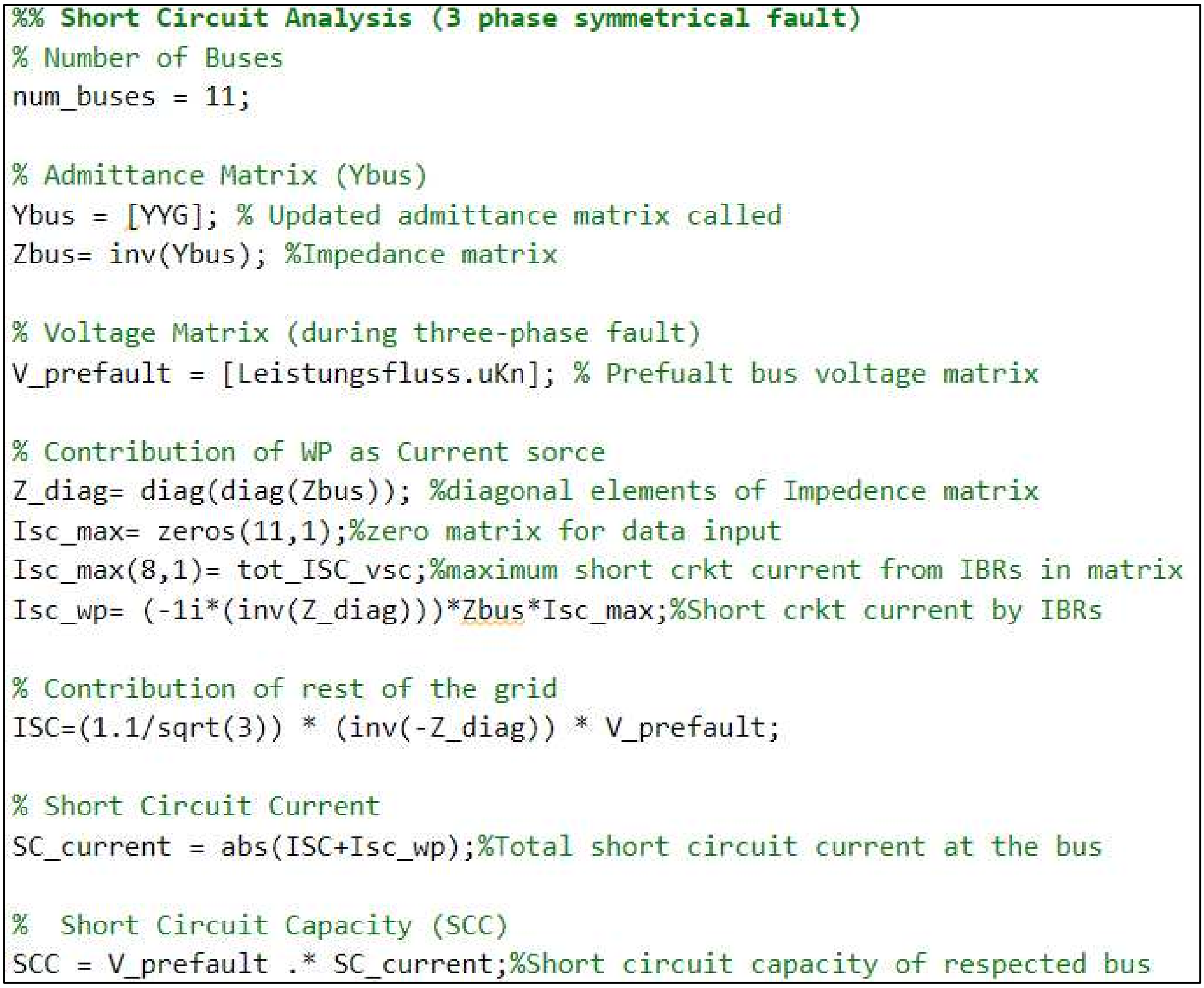
3.2.3 Short Circuit Analysis: Short Circuit Current and Short Circuit Capacity Calculation

In Section 3.1, a specialized MATLAB code is developed to calculate short circuit current using equation (3.1). This code plays a crucial role in determining the maximum short circuit current from IBRs. After this calculation, the total short circuit current is found by assuming a balanced three-phase (3ph) fault scenario at the bus.

Digging deeper into the analysis, the focus shifts to computing SCC . This essential metric indicates the maximum apparent power a bus can contribute or absorb during a short circuit fault. The SCC serves as a measure of the bus's ability to handle electrical power flow under short circuit conditions, expressed in MVA. This expression is particularly significant in evaluating the overall strength of the power system. The SCC can be represented as:

$$SCC = U_{bus} * I_{sc}$$

SCC will be further utilized to calculate SCR and further WSCR.



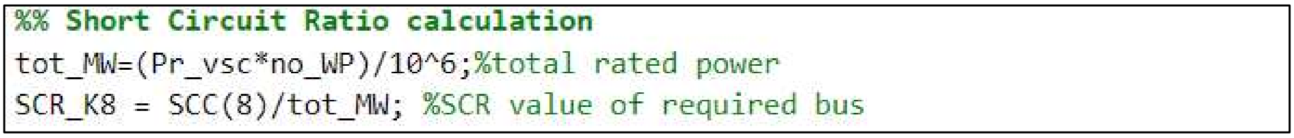
```
%% Short Circuit Analysis (3 phase symmetrical fault)
% Number of Buses
num_buses = 11;

% Admittance Matrix (Ybus)
Ybus = [YYG]; % Updated admittance matrix called
Zbus= inv(Ybus); %Impedance matrix

% Voltage Matrix (during three-phase fault)
V_prefault = [Leistungsfluss.uKn]; % Prefualt bus voltage matrix

% Contribution of WP as Current sorce
Z_diag= diag(diag(Zbus)); %diagonal elements of Impedence matrix
Isc_max= zeros(11,1);%zero matrix for data input
Isc_max(8,1)= tot_ISC_vsc;%maximum short crkt current from IBRs in matrix
Isc_wp= (-1i*(inv(Z_diag)))*Zbus*Isc_max;%Short crkt current by IBRs

% Contribution of rest of the grid
ISC=(1.1/sqrt(3)) * (inv(-Z_diag)) * V_prefault;

% Short Circuit Current
SC_current = abs(ISC+Isc_wp);%Total short circuit current at the bus

%  Short Circuit Capacity (SCC)
SCC = V_prefault .* SC_current;%Short circuit capacity of respected bus
```

Figure 3.5: MATLAB code- Short Circuit Current and Short Circuit Capacity Calculation

The developed code will quantify the short circuit current and SCC of each bus assuming the 3ph fault at that respective bus.

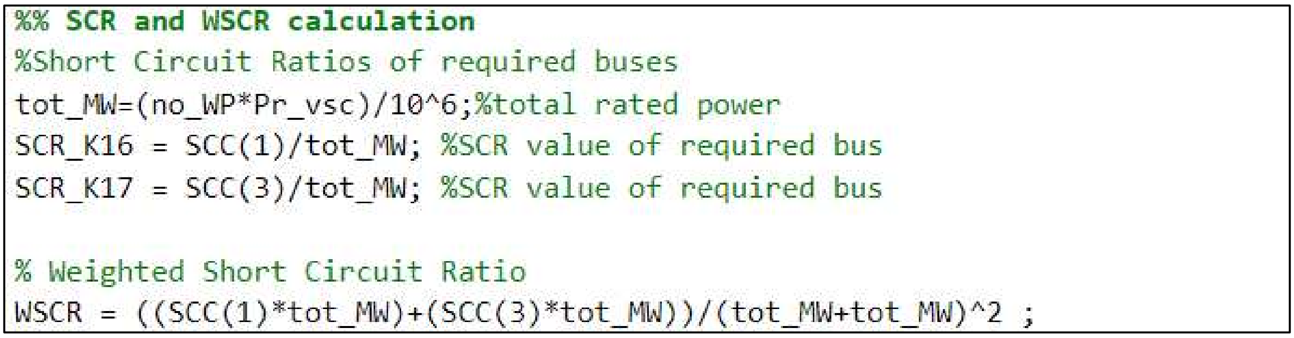
3.2.4 Computation of SCR and WSCR

The concluding phase of this MATLAB program involves the evaluation of SCR and subsequently WSCR. Following the guidelines in Section 2.2, the analysis will focus exclusively on POIs or buses housing IBRs. These particular buses are singled out due to their lower inertia and restricted overcurrent capabilities. This simplifying assumption is adopted to streamline the study, facilitating a more straightforward and comprehensible analysis.



```
%% Short Circuit Ratio calculation
tot_MW=(Pr_vsc*no_WP)/10^6;%total rated power
SCR_K8 = SCC(8)/tot_MW; %SCR value of required bus
```

Figure 3.6: MATLAB code- Evaluation of Short Circuit Ratio of required bus



```
%% SCR and WSCR calculation
%Short Circuit Ratios of required buses
tot_MW=(no_WP*Pr_vsc)/10^6;%total rated power
SCR_K16 = SCC(1)/tot_MW; %SCR value of required bus
SCR_K17 = SCC(3)/tot_MW; %SCR value of required bus

% Weighted Short Circuit Ratio
WSCR = ((SCC(1)*tot_MW)+(SCC(3)*tot_MW))/(tot_MW+tot_MW)^2 ;
```

Figure 3.7: MATLAB code- Evaluation of Weighted Short Circuit Ratio*

*This code is from other test grid having two POIs with IBRs

3.3 Allocation of Synchronous Condensers

SCs play a crucial role in enhancing system strength by elevating short circuit levels [12]. These devices offer additional advantages, such as robust overload capability, effective reactive power support during low voltage conditions, and the operation without introducing harmonics [13].

To provide a comprehensive understanding of the optimal allocation of SCs in the power system, a systematic protocol has been meticulously devised. The proposed methodology unfolds through a systematic step-by-step process illustrated in Figure 3.7, where the optimal ratings and locations for SCs are sought. The procedure commences by incrementally introducing synchronous condensers, each with a specified step size, at candidate locations, followed by the computation of the WSCR. Once all candidate locations undergo evaluation, the synchronous condenser configuration resulting in the highest WSCR is documented. This iterative approach aims to continually enhance the system's strength for improved performance.

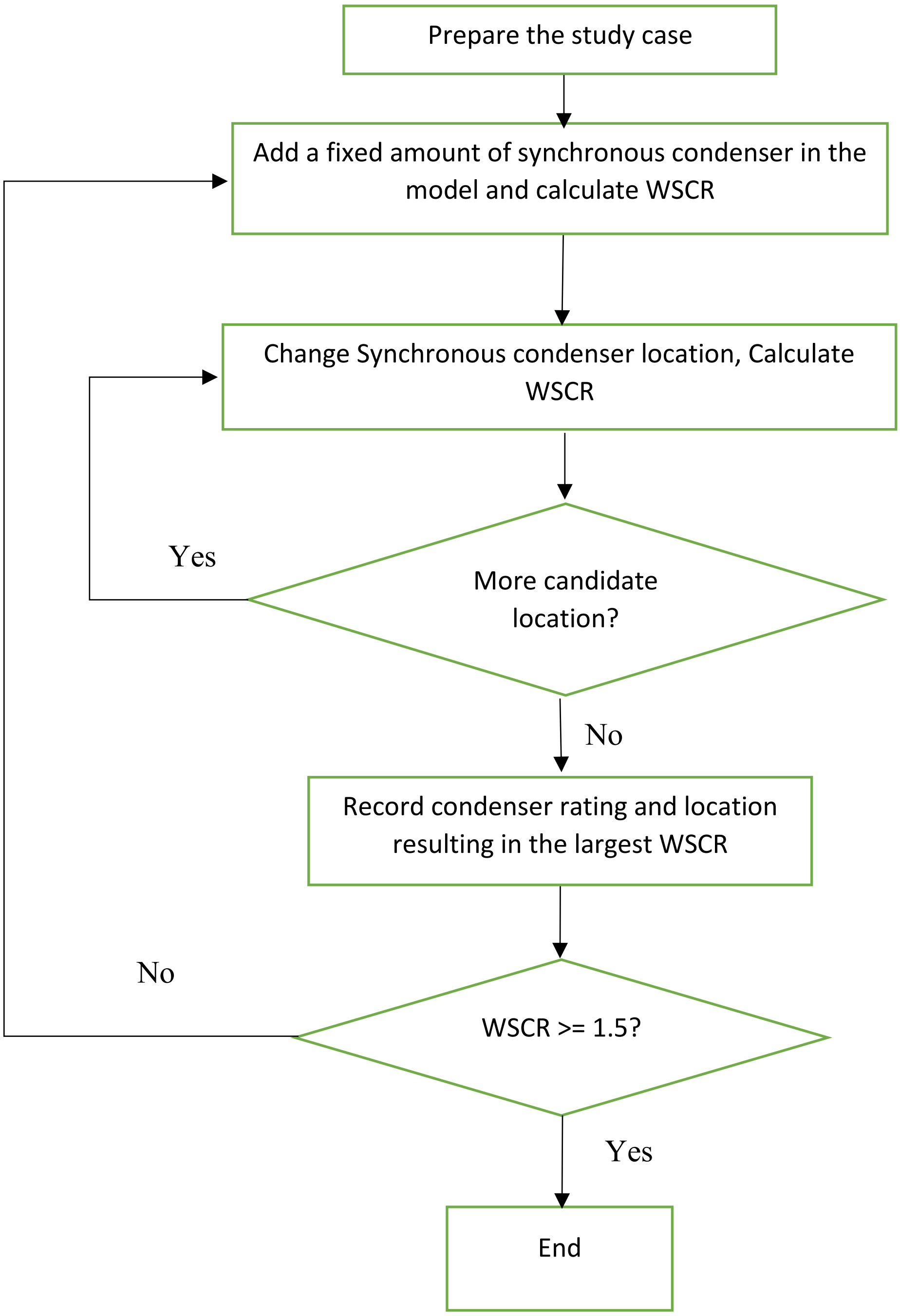


Figure 3.8: Flow chart in order to find the Optimal Location for SCs

As per [9], maintaining a minimum WSCR of 1.5 is considered desirable to ensure voltage stability and provide a sufficient stability margin within the power system. Achieving this optimal WSCR value might necessitate the installation of numerous or sizable SCs. An essential query for transmission planning engineers revolves around determining the optimal ratings and locations for these synchronous condensers to meet WSCR requirements effectively. While a straightforward solution might involve installing all necessary synchronous condensers at the weakest POI, a more favorable approach, from the perspective of WSCR, involves a dispersed solution. This distributed placement strategy is considered more advantageous in enhancing the overall WSCR across the power system.

It's crucial to acknowledge that the obtained synchronous condenser rating and location are based on the assumption of full interaction between IBRs. This ensures the necessary minimum system strength for worst-case scenarios and provides a stability margin. However, for a more nuanced understanding of dynamic responses, especially meeting specific criteria, dynamic simulations employing detailed models of all involved devices are recommended.

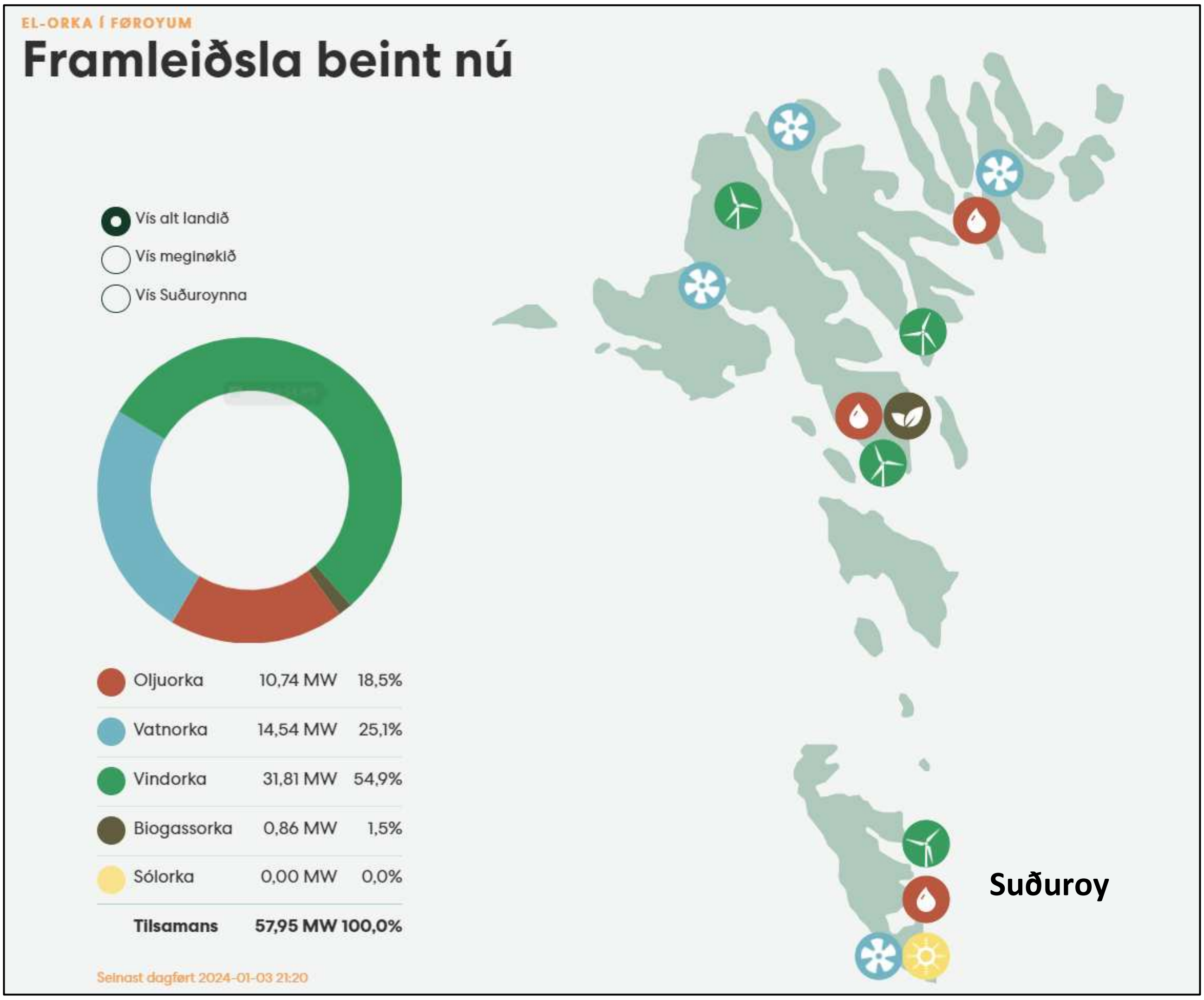
4 Implementation of MATLAB Algorithm for Synchronous Condenser Allocation

The implemented MATLAB algorithm leverages grid data obtained from load flow studies for practical application on the power system. In this chapter, the assessment of grid strength, focusing on the identification of the weakest POI, takes precedence. Subsequently, to enhance the system strength, a new SC will be strategically installed at the identified weakest POI, involving modifications to the grid data derived from load flow studies. This refined dataset will then undergo reapplication in the MATLAB code for the recalibration of SCR and WSCR values. The ensuing chapter will delve into a comparative analysis of the calculated results.

4.1 Suðuroy Power System

Suduroy, situated to the south of the Faroe Islands, is an island with a microgrid featuring a power generation mix including diesel generation, hydropower, and a small wind farm. Currently, a collaborative project is underway between the Faroe Islands grid operators and the Institute for Electrical Energy Systems (IFES) at Leibniz University Hannover. The project focuses on load flow studies and power system stability analysis. The grid operators in the Faroe Islands are in the process of transitioning from conventional diesel-powered synchronous generators to a more IBRs-oriented system.

As part of this ongoing collaboration, the Faroe Island grid operators are exploring solutions to address the challenges arising from the decommissioning of alternators, particularly in terms of loss of inertia and reactive power stability. SCs have emerged as a potential enhancement solution to compensate for these losses. The current research is an integral component of this collaborative project, contributing valuable insights and analyses to support the transition towards a more IBR-centric power system in the Faroe Islands.



EL-ORKA Í FØROYUM

Framleiðsla beint nú

● Vís alt landið
○ Vís meginøkið
○ Vís Suðuroynna

🟥 Oljuorka	10,74 MW	18,5%
🟦 Vatnorka	14,54 MW	25,1%
🟩 Vindorka	31,81 MW	54,9%
● Biogassorka	0,86 MW	1,5%
🟨 Sólorka	0,00 MW	0,0%
Tilsamans	**57,95 MW**	**100,0%**

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[14]

Figure 4.1: Total power generation from various resources in the Faroe Islands.

The MATLAB code, meticulously developed for this study, has been executed using data derived from load flow studies conducted on the Suduroy grid. The implementation involves the calculation of short circuit currents and capacities for each bus, assuming a three-phase symmetrical fault at the respective bus. A subsequent step includes the computation of the SCR specifically for Bus 9, identified as the weakest POI due to its inclusion of a set of IBRs, represented by a wind farm. This tailored analysis aims to assess the system strength, emphasizing the critical role of IBRs in influencing the overall power system dynamics.

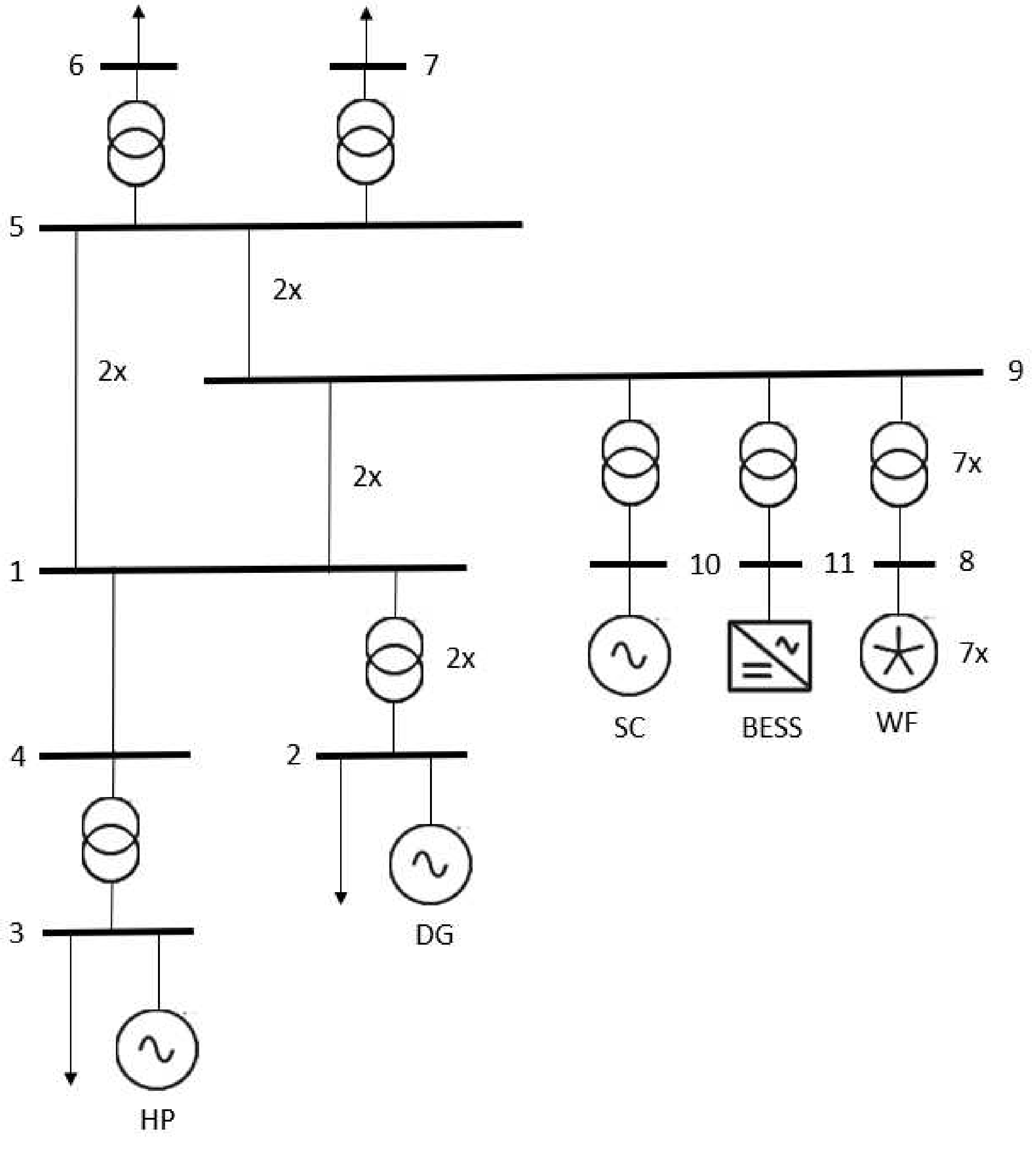


Figure 4.2: Simplified Single Line Diagram of Suduroy Island Grid

Bus number	**Short circuit current (kA)**	**Short circuit capacity (MVA)**
1	2.0443	42.9302
2	2.9495	30.9694
3	2.0035	21.0364
4	1.8939	39.7722
5	1.9953	41.9014
6	2.3872	25.0658
7	2.3874	25.0678
8	84.2763	33.7105
9	2.1428	44.9986
10	7.1439	75.0110
11	58.9110	23.5644

SCR_K9	6.98

Table 4.1: Short circuit analysis of the system and SCR of POI (Bus 9)

After running the data through the algorithm, SCR value calculated came around 6.98.

4.1.1 Modification in Grid Data to Incorporate new SC

Upon successfully calculating the SCR value at the weakest POI, the next step involves the virtual installation of an additional SC. This process requires the modification of the grid data obtained from the Load Flow study analysis. To virtually introduce the new SC into the grid, an additional bus, denoted as the 12th Bus, is incorporated into the system.

This introduction prompts updates to key matrices such as the Nodal Admittance Matrix [YKK], Terminal Admittance Matrix [YT], and Node Incidence Matrix [KKT]. Specifically, KKT undergoes modification to incorporate an additional terminal for the 12th Bus. The updating of YT and YKK involves the addition of a transformer and a SC to account for the new bus in the system. These updates reflect the dynamic adjustments made to simulate the installation of the SC and pave the way for subsequent analyses of the modified system.

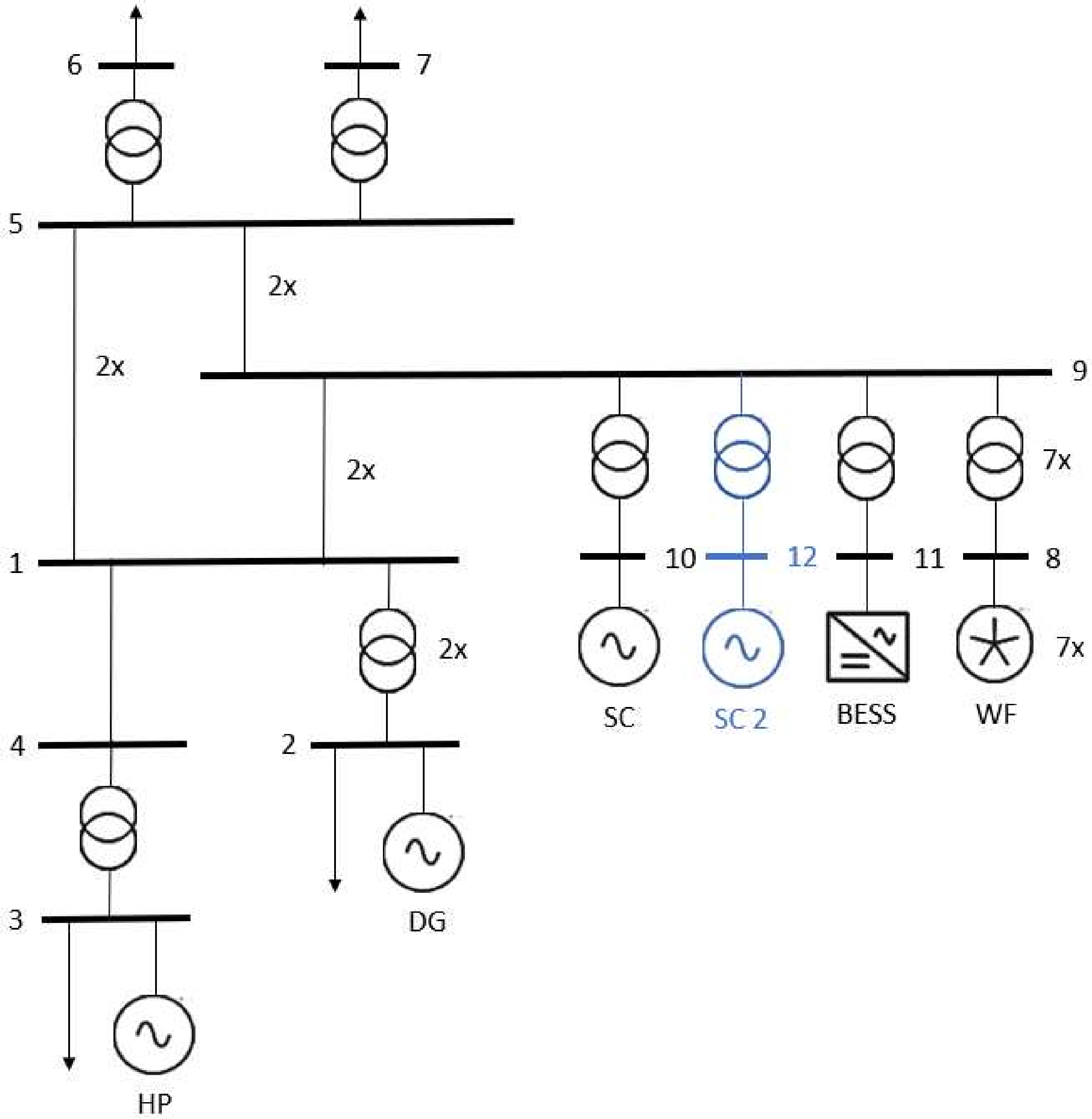
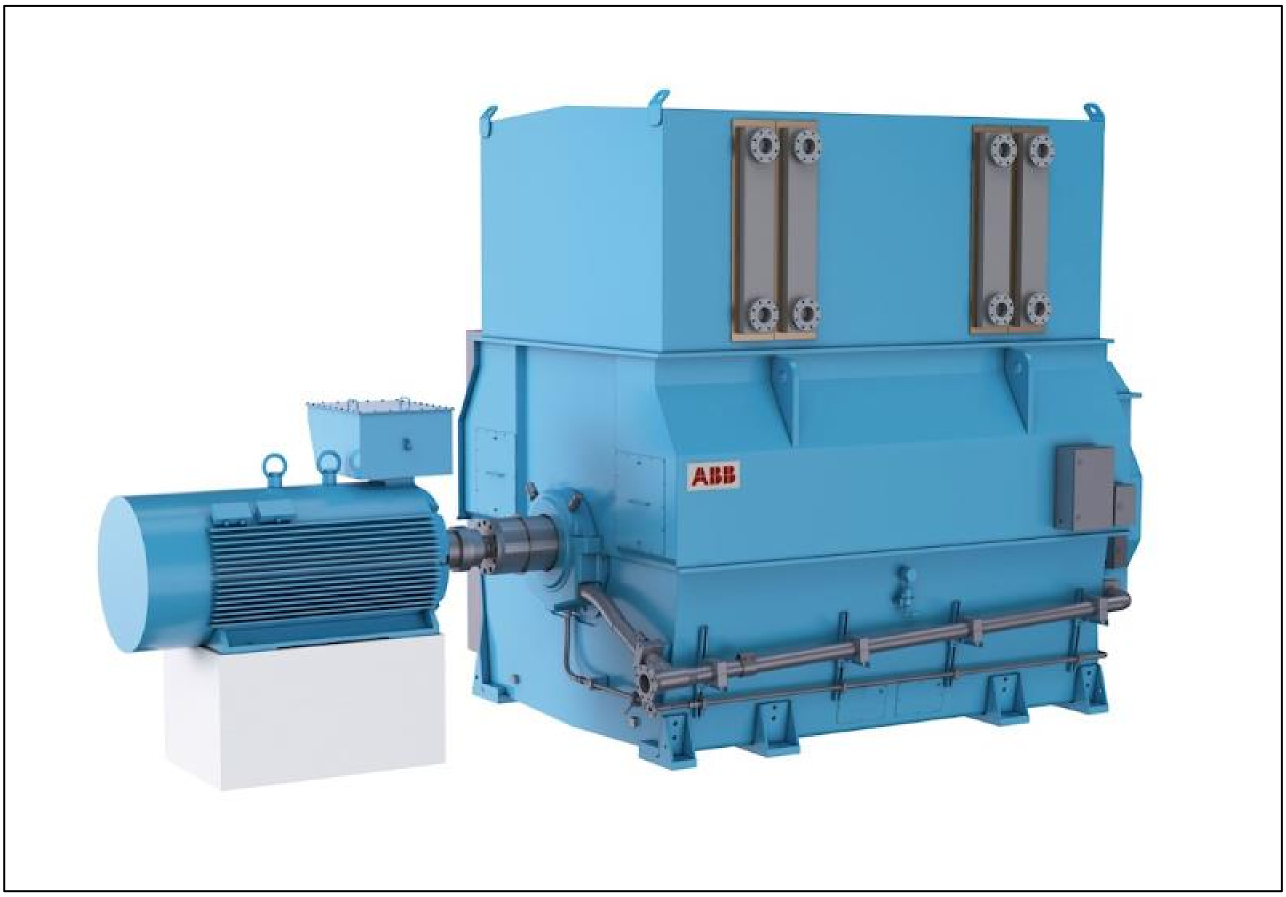


Figure 4.3: Modified Single Line Diagram of Suduroy Island Grid after incorporation of additional SC



[15]

Figure 4.4: ABB 8 MVA Synchronous Condenser installed in Suduroy grid

Bus number	Short circuit current (kA)	Short circuit capacity (MVA)
1	9.3961	197.3173
2	6.2962	66.1098
3	5.7591	28.4627
4	8.9159	120.9416
5	4.8274	187.2343
6	4.8289	50.6873
7	188.4799	50.7038
8	15.4778	75.3920
9	13.0975	325.0333
10	123.1246	49.2498
11	6.6242	69.5539
12	69.5539	6.6242

SCR_K9	15.6091

Table 4.2: Short circuit analysis of the system and SCR of POI (Bus 9) after installing new SC at bus 12

4.2 17-Bus 220kV Test System

For further verification of the functioning of the algorithm, grid data from 17-bus 220kV Test System is taken. This test system was formulated for frequency stability analysis for IBRs (wind turbines) integrated system at IFES department, Leibniz University Hannover [16].

Four load buses (K4, K10, K11, K16) are supplied by three synchronous generators and two wind parks (WP) through a transmission grid. WP1 comprises 80 DFIG-based WTs and WP2 consists of 80 FSC-based WTs each with a rated active power of 2 MW. To determine the nodal voltages and powers at the considered operating point, a Newton–Raphson-based power flow calculation is conducted [16].

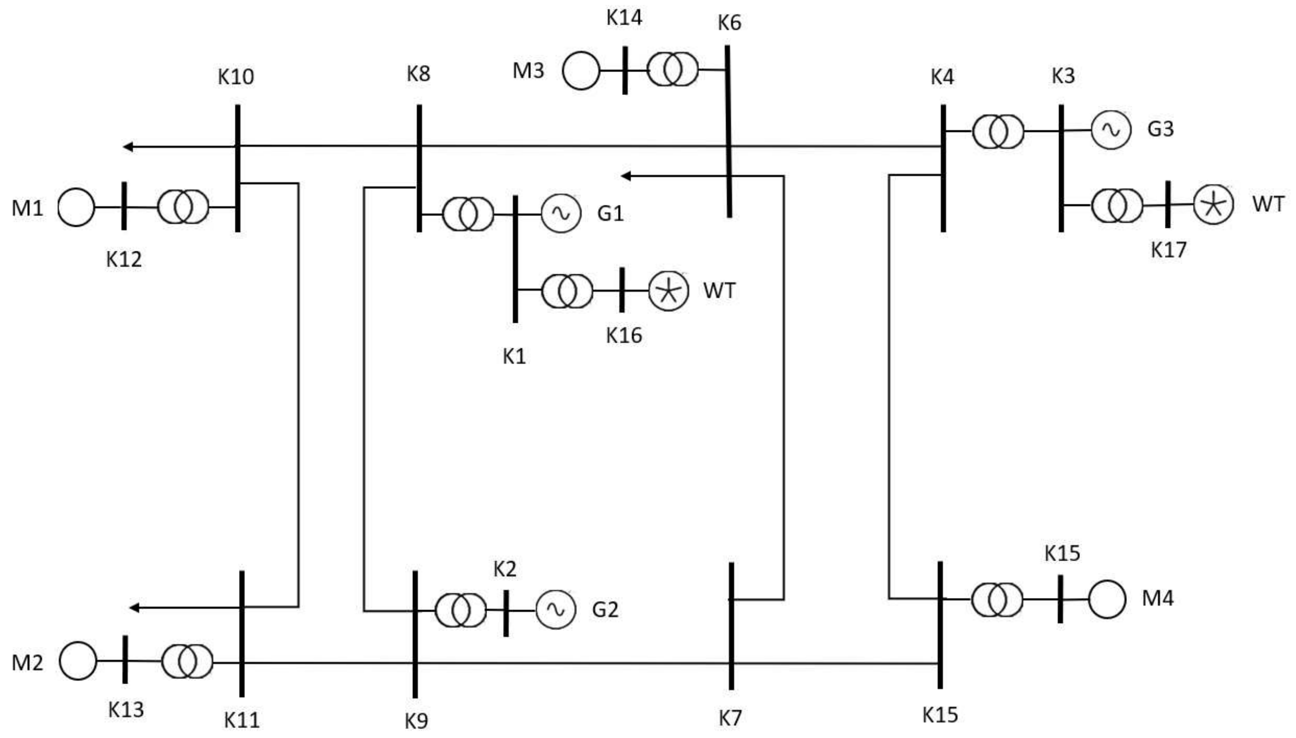


Figure 4.5: Single Line Diagram of 17-Bus 220kV Test System

Bus number	**Short circuit current (kA)**	**Short circuit capacity (MVA)**
1	96.1179	1922.3574
2	93.2346	1864.6915
3	93.4991	1869.9823
4	4.7251	1795.5249
5	4.3957	1670.3655
6	4.7972	1822.9308
7	4.7116	1790.4058
8	5.0202	1907.6630
9	5.0080	1903.0524
10	4.3537	1654.4194
11	4.3511	1653.4236
12	179.8618	1133.1219
13	179.8324	1132.9441
14	191.9367	1209.2012
15	180.9580	1140.0359
16	1495.5542	1031.9324
17	1477.3345	1019.3608

SCR_K1	6.4496
SCR_K3	6.3710
WSCR	3.2051

Table 4.3: Short circuit analysis of the 17-bus power system with SCR and WSCR

The MATLAB algorithm initially designed for the Suduroy grid has been refined by adapting it to the 17-bus 220kV test system. This update necessitates modifications to the data inputs and computational parameters to ensure alignment with the characteristics and specifications of the new test system. Furthermore, given the presence of two POIs within this system, the WSCR calculations are extended for this data. This assessment enhances the accuracy and granularity of the grid strength evaluation, providing a more comprehensive insight into the system's performance and resilience.

4.2.1 Modification in Grid Data to Incorporate New SC at the Weakest POI

Upon rigorous evaluation of the SCRs for both POIs, it is imperative to implement the SC at the POI with the lesser SCR value, indicating a comparatively weaker system strength. Based on the data presented, Bus 3 emerges as the location with the inferior SCR. Consequently, the integration of the SC will be executed at this specific bus. Subsequent to this modification, a reassessment of the grid strength will be conducted to ascertain the effectiveness and impact of the SC installation on enhancing the system's robustness and stability.

To accommodate the integration of the SC and the associated transformer, it is essential to augment the existing grid data. This will necessitate the introduction of a new bus, necessitating modifications to the Node Incidence matrix (KKT). Additionally, to accurately reflect the changes brought about by the SC and transformer installation, adjustments will be made to the Nodal Admittance matrix (YKK) and the Terminal Admittance matrix (YT). These modifications ensure that the updated matrices provide a comprehensive representation of the grid's configuration post-integration of the SC and transformer.

In the absence of specific datasheets pertaining to the SC and transformers for the test system, data from the Suduroy grid serves as a foundational reference. Given that Suduroy operates at a smaller scale compared to the 17-bus 220kV test system, adjustments to the admittance values for both the SC and transformer have been empirically made. These modifications aim to align the empirical values more closely with the operational characteristics and requirements of the larger test system, ensuring a more accurate representation in the simulations and analyses.

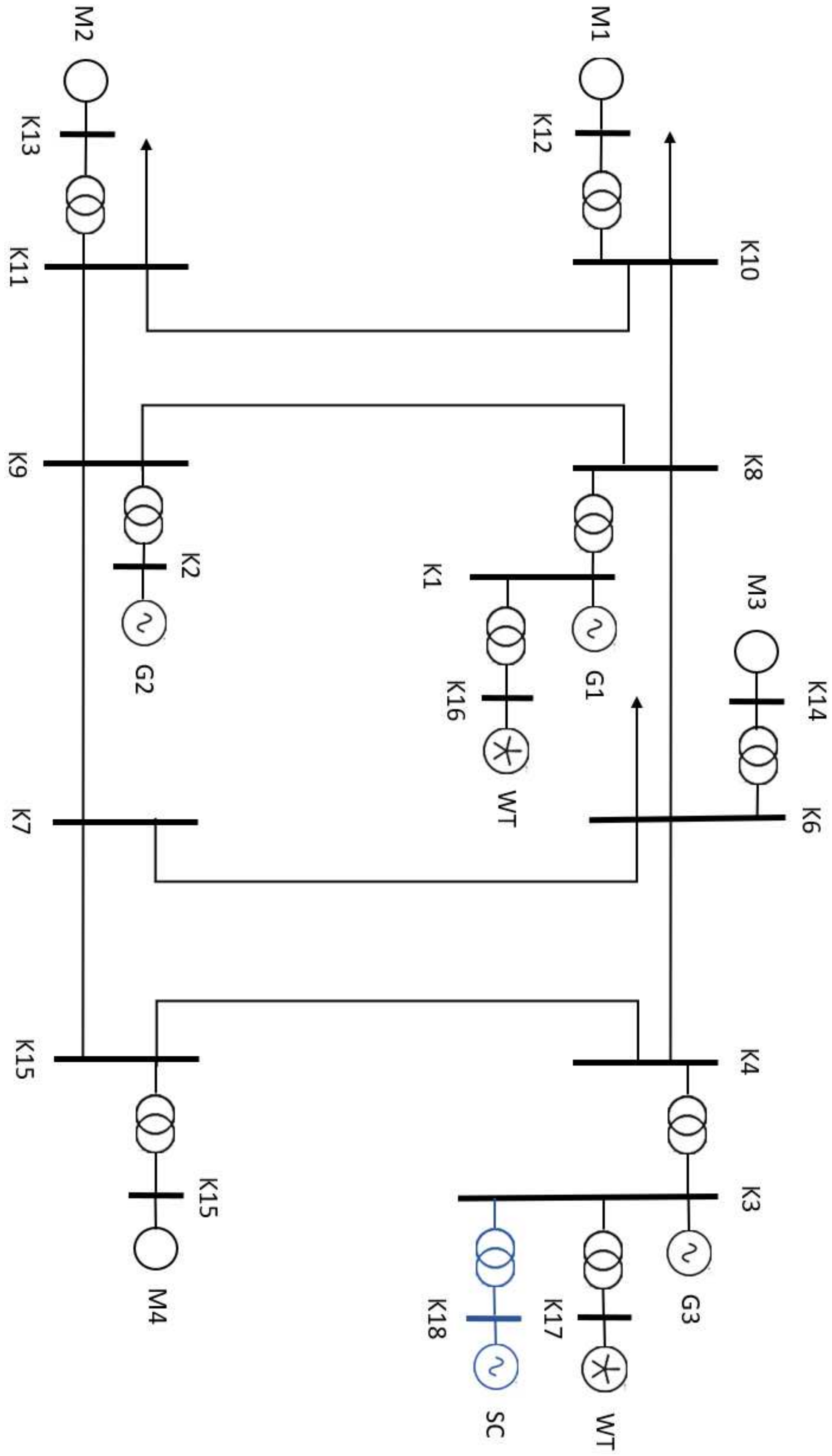


Figure 4.6: Modified Single Line Diagram of 17-bus 220kV test system after incorporation of additional SC

Bus number	**Short circuit current (kA)**	**Short circuit capacity (MVA)**
1	96.5000	1930.0007
2	93.5981	1871.9620
3	95.9637	1919.2743
4	4.7980	1823.2449
5	4.4526	1691.9886
6	4.8557	1846.3169
7	4.7692	1812.2799
8	5.0755	1928.6721
9	5.0624	1923.7262
10	4.3959	1670.4602
11	4.3931	1669.3855
12	181.1156	1141.0282
13	181.0812	1140.8118
14	193.6421	1219.9451
15	182.6238	1150.5302
16	1497.7429	1033.4426
17	1494.0362	1030.8850
18	11.2086	117.6899

SCR_K1	12.0625
SCR_K3	11.9955
WSCR	6.0145

Table 4.4: Short circuit analysis of the modified 17-bus power system with SCR and WSCR

5. Results

The algorithm has been executed using the grid data detailed in Chapter 4. Comprehensive short circuit analyses and subsequent SCR calculations were carried out and validated. This chapter delves into the outcomes observed post-execution of the MATLAB script on the aforementioned grid datasets, encompassing both scenarios: before and after the installation of the SC. The observed changes in the SCR or WSCR values serve as pivotal indicators for gauging alterations in the grid's resilience and strength. Beyond merely focusing on the optimal placement of SC within IBR dominated systems, this research also lays the groundwork for comprehensive investigations into the calculation methodologies for short circuit currents within such systems.

The results obtained aim to tackle the challenge of insufficient overcurrent capabilities in Power Electronic Converters. These findings will empower the grid operators in the Faroe Islands to evaluate the grid strength across the microgrids of the different islands. Furthermore, it will guide them in pinpointing the optimal locations for SC installations, especially as they transition from traditional generators to Inverter-Based Resources (IBRs).

Before delving into the results, this chapter elucidates the critical hypotheses and assumptions formulated for the experiment's execution. These assumptions were essential to streamline the intricate short circuit analysis, ensuring that the SCR and WSCR emerged as the most fitting metrics for assessing grid strength.

5.1 Hypothesis and assumption

In the realm of complex engineering analyses, hypotheses and assumptions serve as foundational pillars upon which research methodologies are constructed. As we delve into the complications of short circuit analysis within our study, it becomes imperative to elucidate the underlying assumptions and hypotheses that underpin our investigative approach. This chapter meticulously delineates the foundational principles and suppositions that were adopted to streamline our experiment. By setting forth these assumptions, our aim was not only to simplify the complex aspects of short circuit analysis but also to establish the SCR and WSCR as robust and optimal metrics for gauging grid strength. Through a comprehensive exposition of these hypotheses and assumptions, readers will gain a clearer understanding of the methodological choices made and the rationale behind them, paving the way for a more informed evaluation of the subsequent results.

5.1.1 Assumption 1: Disregarding Static Loads in Fault Analysis

In the analysis conducted for fault scenarios, a foundational assumption is made regarding the conditions under which the analysis is conducted. Specifically, the study operates under the premise that static loads within the system can be omitted from consideration. This decision is rooted in the need to isolate and understand the pure dynamics of the fault itself, without the complicating factors introduced by varying load conditions. Consequently, when computing fault current values, the analysis prioritizes the pre-fault voltage conditions as the primary determinant.

5.1.2 Assumption 2: Ignoring Reactance Values of IBRs in Fault Analysis

In the pursuit of a streamlined and focused analysis, a pivotal assumption is made concerning the IBRs within the power system. Specifically, for the purposes of fault analysis, the reactance values associated with IBRs are deliberately disregarded. This simplification aims to reduce the computational complexities and isolate the primary contributions to fault behaviors. By excluding the reactance values of IBRs, the analysis can more directly evaluate the impact of other system components on fault conditions. However, it's essential to note that this assumption might lead to a slight deviation from real-world scenarios, as the reactance values of IBRs can indeed influence fault currents.

5.1.3 Assumption 3: Exclusion of Economic Considerations in Synchronous Condenser Allocation

In the ambit of this research, a deliberate decision has been made to exclude the economic dimension related to the allocation SCs. While the study primarily emphasizes the technical merits, as evidenced by the SCR and WSCR values pinpointing the weakest POI, it's crucial to recognize that real-world scenarios entail multifaceted considerations. Merely identifying the weakest POI based on technical parameters does not necessarily translate to the most cost-effective or efficient allocation strategy.

In practical applications, the decision to install SCs is influenced not only by technical imperatives but also by economic constraints and objectives. The actual cost implications associated with deploying SCs can significantly reshape the optimal allocation strategy. Thus, by sidelining the economic aspects in this analysis, the research offers a focused yet potentially limited perspective. While the findings elucidate the technical convolutions, they form just one facet of a broader decision-making landscape. Future endeavors might benefit from integrating economic metrics to present a more comprehensive and pragmatic allocation strategy for SCs.

5.1.4 Assumption 4: Introduction of Additional Synchronous Condenser for Algorithm Validation in Suduroy Power System

Within the framework of the Suduroy grid data analysis, a noteworthy assumption is made regarding the introduction of an additional SC. Specifically, even when the calculated SCR for the grid surpasses the conventional threshold of 3—indicating robust system strength—a second SC with a commensurate rating is incorporated into the system.

This decision isn't predicated on an actual operational need stemming from system inadequacy. Instead, the primary rationale behind this addition is to rigorously validate and verify the functionality and accuracy of the developed MATLAB algorithm.

5.1.5 Assumption 5: Empirical Adaptation of Synchronous Condenser and Transformer Parameters for Testing in 17-bus System

In the context of this research, a crucial assumption is made concerning the adaptation of equipment parameters from the Suduroy grid data to the 17-bus test system. Specifically, due to the unavailability of specific datasheets for the intended SC rating, the decision is made to apply the SC and transformer parameters derived from the Suduroy grid directly to the 17-bus test system.

This transposition, while facilitating the testing process, necessitates an empirical adjustment of certain parameters to ensure compatibility and accuracy. Notably, the admittance values—integral to the operation and performance of both the transformer and SC—are empirically modified.

However, it is important to acknowledge that despite these empirical modifications, the results obtained may not fully align with what would be anticipated had the system been equipped with SC and transformer units rated precisely for the 17-bus configuration. This discrepancy underscores the inherent limitations and potential trade-offs associated with empirical adjustments in research settings, emphasizing the importance of these assumptions in contextualizing the study's findings.

5.2 Results and observation

In this pivotal section, we embark on a comprehensive exploration of the experiment's results, unfolding the intricate dynamics of the Suduroy grid and the 17-bus test system. The meticulously crafted MATLAB algorithm is set into motion, scrutinizing the pre-installation and post-installation scenarios of SCs. The comparative analysis focuses on the SCR and WSCR values, pivotal metrics that serve as reliable indicators of grid strength. By navigating through SCR values at different POIs in both the Suduroy and 17-bus test systems, this section elucidates the transformative impact of SC installation on the overall power system strength. Through meticulous observations and analytical scrutiny, valuable insights emerge, providing a basis for a nuanced understanding of the grid's dynamic behavior. This comparison lays the groundwork for informed decision-making in power system planning, offering a valuable lens through which to assess the effectiveness of SC integration in enhancing the resilience and stability of the examined power systems.

5.2.1 Comparative Result Analysis of Suduroy Power System

The section contrasts the grid strength before and after SC installation in Suduroy.

Bus number	**Short circuit current pre-SC installation (kA)**	**Short circuit current post-SC installation (kA)**
1	2.0443	9.3961
2	2.9495	6.2962
3	2.0035	5.7591
4	1.8939	8.9159
5	1.9953	4.8274
6	2.3872	4.8289
7	2.3874	188.4799
8	84.2763	15.4778
9	**2.1428**	**13.0975**
10	7.1439	123.1246
11	58.9110	6.6242
12	-	69.5539

Table 5.1: Comparative Analysis of pre and post installation short circuit current of Suduroy grid data

Bus number	Short circuit capacity pre-SC installation (MVA)	Short circuit capacity post-SC installation (MVA)
1	42.9302	197.3173
2	30.9694	66.1098
3	21.0364	28.4627
4	39.7722	120.9416
5	41.9014	187.2343
6	25.0658	50.6873
7	25.0678	50.7038
8	33.7105	75.3920
9	**44.9986**	**325.0333**
10	75.0110	49.2498
11	23.5644	69.5539
12	-	6.6242

SCR_K9 pre-SC installation	6.98
SCR_K9 post-SC installation	15.6091

Table 5.2: Comparative Analysis of pre and post installation SCC and SCR of Suduroy grid data

Based on the provided table comparison, there's a notable enhancement in the short circuit capacity of the POI after integrating an extra SC. The capacity notably rose from 44.9986 MVA to 325.0333 MVA. This augmentation correspondingly amplified the SCR at bus 9, elevating it from 6.98 to 15.61. Such a pronounced boost underscores the bolstered resilience of the grid. Moreover, beyond merely supplying reactive power, the SC adeptly manages the surge in current during fault scenarios—a challenge previously unaddressed by the IBRs.

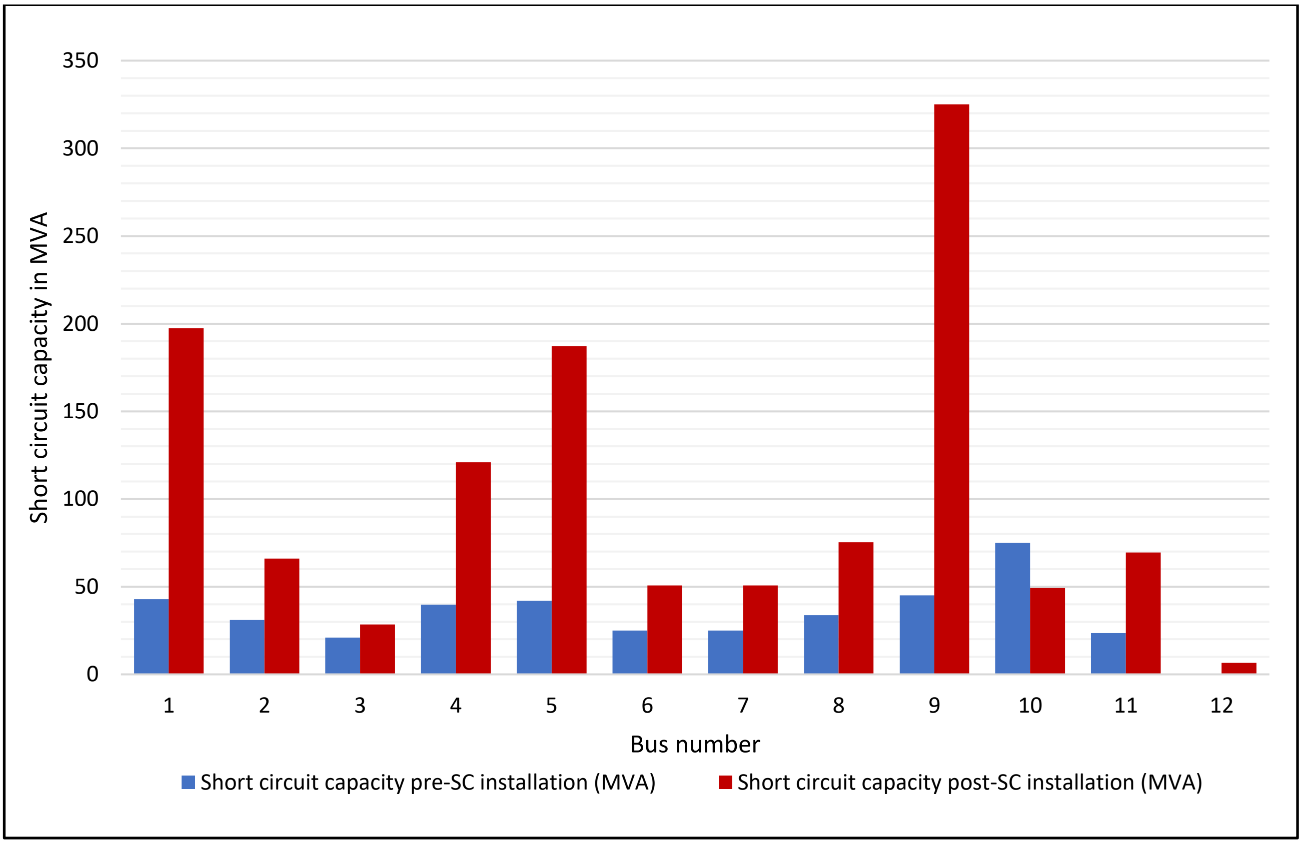


Figure 5.1: Comparison chart of pre and post installation short circuit capacity of Suduroy grid data

5.2.2 Comparative Result Analysis of 220 kV 17-bus Test system

The obtained results from the execution of the MATLAB algorithm for the 17-bus test system are rigorously compared in both pre- and post-installation of SC scenarios. This comparative analysis aims to elucidate the practical implications and outcomes arising from the implementation of the algorithm, shedding light on the effectiveness of the SC in enhancing the system's strength and resilience.

Bus number	**Short circuit current pre-SC installation (kA)**	**Short circuit current post-SC installation (kA)**
1	96.1179	96.5000
2	93.2346	93.5981
3	**93.4991**	**95.9637**
4	4.7251	4.7980
5	4.3957	4.4526
6	4.7972	4.8557
7	4.7116	4.7692
8	5.0202	5.0755
9	5.0080	5.0624
10	4.3537	4.3959
11	4.3511	4.3931
12	179.8618	181.1156
13	179.8324	181.0812
14	191.9367	193.6421
15	180.9580	182.6238
16	1495.5542	1497.7429
17	1477.3345	1494.0362
18	-	11.2086

Bus number	**Short circuit capacity pre-SC installation (MVA)**	**Short circuit capacity post-SC installation (MVA)**
1	1922.3574	1930.0007
2	1864.6915	1871.9620
3	**1869.9823**	**1919.2743**
4	1795.5249	1823.2449
5	1670.3655	1691.9886
6	1822.9308	1846.3169
7	1790.4058	1812.2799
8	1907.6630	1928.6721
9	1903.0524	1923.7262
10	1654.4194	1670.4602
11	1653.4236	1669.3855
12	1133.1219	1141.0282
13	1132.9441	1140.8118
14	1209.2012	1219.9451
15	1140.0359	1150.5302
16	1031.9324	1033.4426
17	1019.3608	1030.8850
18	-	117.6899

Parameters	**Pre-SC installation**	**Post-SC installation**
SCR_K1	6.4496	12.0625
SCR_K3	6.3710	11.9955
WSCR	3.2051	6.0145

Table 5.3: Comparative Analysis of pre and post installation SCC and SCR of 17-bus Test system

The evaluation of the 17-bus test system, employing the customized MATLAB algorithm, has yielded insights into the consequential improvements in grid strength. Adhering to Assumption 5.1.5, where SC ratings were empirically adjusted to match the grid's scale, the outcomes at the identified POI, bus K1, and its neighboring counterpart, bus K3, unveil a notable enhancement in the SCR. Initially standing at 6.4496, the SCR at bus K1 experienced a substantial surge, reaching 12.0625 post-SC installation. This enhancement implies a considerable bolstering of the grid's ability to withstand short-circuit conditions at this specific location.

Moreover, the neighboring POI, bus K3, also exhibited an improved SCR following the introduction of the synchronous condenser at bus K1. This interconnected improvement in SCR at different POIs highlights the system-wide impact of the SC installation. WSCR, designed to offer a comprehensive evaluation by considering the impact at all POIs, further supports the observed augmentation. The WSCR escalated from 3.2051 to 6.0145, emphasizing a substantial reinforcement of the grid's overall strength.

Analyzing the progression from our initial assumptions to the tangible outcomes, it becomes evident that the adjusted SCR values post-SC installation reflect a more resilient grid. The refined WSCR provides a holistic metric, considering the weighted impact at multiple POIs, aligning with our objective of evaluating system strength comprehensively. This underscores the algorithm's efficacy in not only pinpointing specific improvements but also capturing the collective influence on the entire system. The empirically adjusted SC ratings, while deviating from a strict theoretical approach, prove pragmatic in achieving the intended grid enhancement. Thus, the detailed analysis corroborates the effectiveness of the devised algorithm and its tangible impact on the 17-bus test system's grid strength.

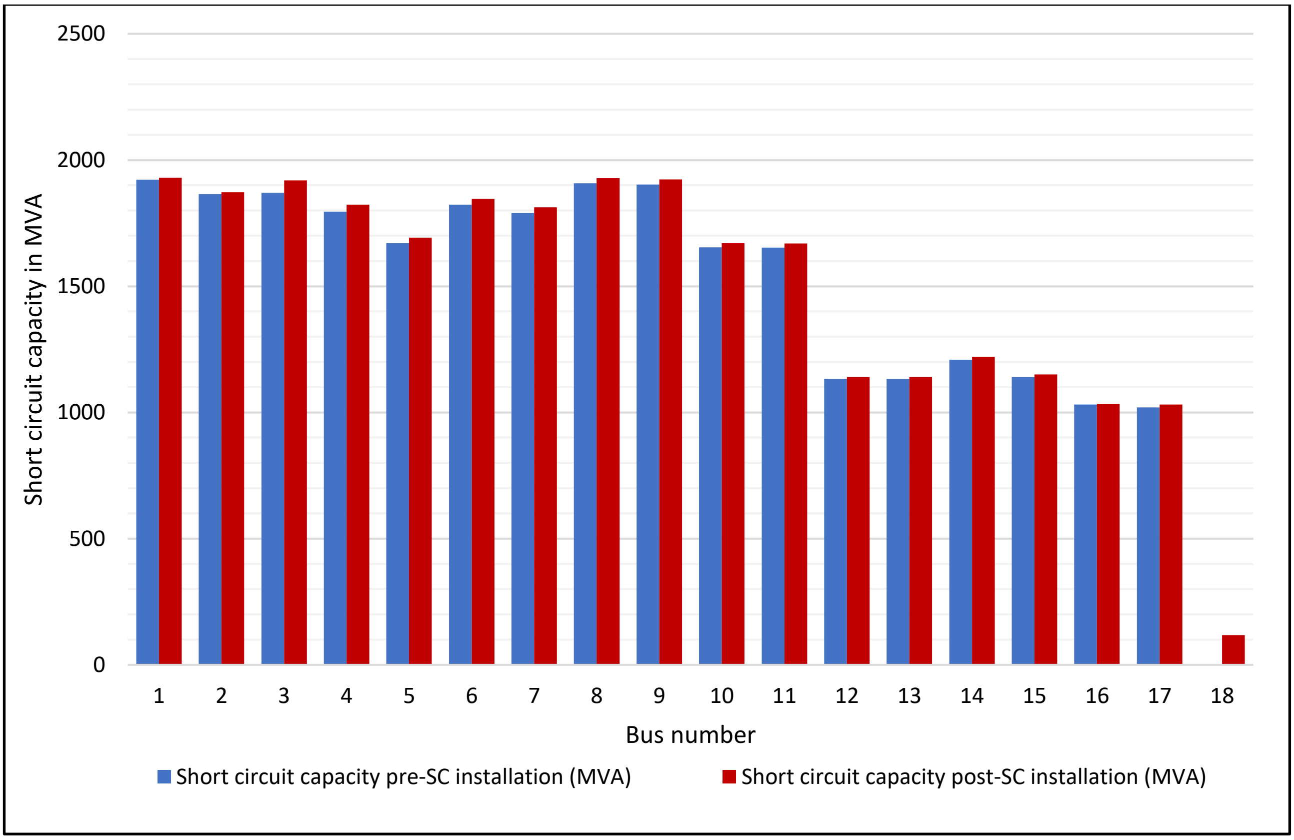


Figure 5.2: Comparison chart of pre and post installation short circuit capacity of 17-bus Test System

6. Conclusions and Future Aspects

The present work has been focused on the optimal allocation of SCs in the grid which is dominated by IBRs. The study of this complex procedure is important for several complications like reactive power control, overcurrent capabilities, grid strength and inertia. The MATLAB algorithm has been developed exploiting resulted grid data from load flow studies made available by IFES, at the Leibniz University Hannover.

In the first part of the work, a literature review has been conducted with the goal of studying and presenting the current knowledge on Grid Strengthening Setup [1], SC performance parameters [2] and SC applications [17] . In particular, the study focused on development of a MATLAB algorithm using SCR and WSCR as indicators of grid strength [3] [4] [6] through short circuit analysis of IBR dominated grid [5] [8] [11].

In conclusion, this thesis embarked on a comprehensive exploration of the integration of SCs into power systems and its implications on system strength. The focal point was the development and application of a specialized MATLAB algorithm, meticulously tailored to analyze short circuit scenarios and evaluate the efficacy of SCs in enhancing system strength. The thesis commenced with a brief understanding of the challenges posed by IBRs, emphasizing their unique fault current characteristics and the need for a refined analysis approach.

The inception of the research elucidated the inadequacies of conventional Short Circuit Ratio (SCR) calculations in capturing the complex dynamics of power systems with IBRs. To address this limitation, the concept of Weighted Short Circuit Ratio (WSCR) was introduced, considering the interactions between IBRs and their collective impact on system strength [9]. The proposal of WSCR, underpinned by a theoretical framework and an empirically developed algorithm, aimed to provide a more accurate representation of system strength in the presence of IBRs.

The methodology section outlines the step-by-step formulation of steady-state short circuit analysis, integrating the SCR and WSCR calculations into the MATLAB algorithm. The algorithm's construction unfolded, incorporating considerations for fault current contributions from both conventional synchronous generators and IBRs as per the formulary provided by IFES Hannover [11]. The empirical modification of IBR parameters for realistic simulations and the exclusion of economic aspects for the sake of simplicity were integral assumptions guiding the algorithm's development.

Application of the algorithm on two distinct power systems – the Suduroy grid and a 17-bus test system [16] – showcased its versatility and effectiveness. The comparative analysis demonstrated a substantial improvement in SCR values at identified POIs after the virtual installation of SCs. The refined WSCR further underscored the grid's enhanced strength in the post-SC scenarios, validating the algorithm's utility in assessing system resilience comprehensively.

In essence, this research contributes to the evolving landscape of power system analysis by addressing the limitations posed by IBRs. The proposed algorithm, although grounded in theoretical frameworks, exhibits its practical efficacy through tangible improvements in SCR and WSCR values. As power systems transition towards increased IBR penetration, this work provides a valuable tool for grid operators and planners to optimize SC installations and fortify the overall strength of the grid.

6.1 Future Aspects of Synchronous Condensers in Power system

The concept of Synchronous condenser is not new. It was invented in 1919 to regulate the system voltage but lost the popularity to FACTs devices such as SVCs and STATCOMs. However, they are now regaining utilization because of the lack of inertia and overcurrent capabilities provided by the FACTs as the power system is being dominated by IBRs. This thesis is paving the way for future aspects of installation of SCs in the power system by defining optimized methods for the allocation of SCs. The Future aspects of SCs includes:

1. **Enhanced Modeling and Simulation**: As power systems evolve with increasing complexity due to the integration of renewable energy

sources, future research can delve deeper into refining the modeling and simulation techniques for synchronous condensers. This will ensure that the behavior and interactions of synchronous condensers in a dynamic grid environment are accurately captured.

2. **Optimized Deployment Strategies**: Building upon the findings of this thesis, there's a need for further studies to develop advanced algorithms that can determine the optimal locations for synchronous condenser installations. By considering both technical parameters and economic factors, grid operators can make informed decisions that maximize system benefits.

3. **Integration with Advanced Grid Technologies**: The advent of smart grids, IoT devices, and advanced control systems offers opportunities for synchronous condensers to play more dynamic roles. Future endeavors could explore how synchronous condensers can synergize with these technologies to enhance grid stability, voltage regulation, and overall reliability.

4. **Exploring Auxiliary Services**: Beyond their traditional role, synchronous condensers can be evaluated for their potential in providing auxiliary services such as frequency regulation, reactive power support, and voltage control. Research in this domain can shed light on the extent to which synchronous condensers can complement or even replace existing auxiliary service providers.

5. **Technological Advancements**: With ongoing advancements in materials science and electrical engineering, there's potential for innovations in synchronous condenser design. This includes the development of more compact, efficient, and cost-effective synchronous condensers that can be seamlessly integrated into existing infrastructures.

6. **Environmental Considerations**: As the global emphasis on sustainable energy solutions intensifies, future research can focus on

assessing the environmental impact of synchronous condensers. This includes evaluating their carbon footprint, exploring potential recycling or repurposing strategies for old units, and investigating alternative materials or designs that minimize environmental degradation.

7. **Training and Skill Development**: With the resurgence of interest in synchronous condensers, there's a growing need for skilled professionals proficient in their operation, maintenance, and troubleshooting. Future initiatives could focus on developing comprehensive training programs and workshops tailored to the evolving needs of the industry.

In closure, while this thesis provides invaluable insights into the role and impact of synchronous condensers in contemporary power systems, the journey towards harnessing their full potential is ongoing. The outlined future aspects offer a roadmap for subsequent research, innovation, and advancements in the realm of synchronous condensers, ensuring their continued relevance and efficacy in the rapidly transforming energy landscape.

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