

Comparative Evaluation of Dynamic Performance of Virtual Synchronous Machine and Synchronous Machines

Md Asif Uddin Khan¹⁺, Qiteng Hong^{1*}, Di Liu¹, Agusti Egea Alvarez¹, Adam Dyśko¹, Campbell Booth¹ and Djaved Rostom²

¹Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, UK

²Network Operability, National Grid ESO, Faraday House, Warwick Technology Park, Warwick, UK

Email: *q.hong@strath.ac.uk and +asif.u.khan@strath.ac.uk

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Abstract

Increasing penetration of converter-interfaced renewable generation has led to significant operational challenges for power systems. Such challenges are mainly caused by the different capabilities and dynamic responses of the converters compared with synchronous machines, e.g. converters do not naturally provide inertia to the system and contribute limited fault level with very different fault characteristics. Virtual Synchronous Machines (VSM) and Synchronous Condensers (SCs) are both considered as promising solutions to address the challenges in operating converter-dominated power systems. This paper presents comprehensive studies for evaluating and comparing the dynamic performance of VSM, SC and Synchronous Generators (SGs), under a range of grid contingency events, which include short circuit faults, frequency disturbances, voltage depression, etc. The studies aim to offer insights on the level of support VSMs can offer to the system as compared with SCs and SGs, and their advantages, potential issues and limitations that need to be considered for a wider application in the system. From the studies, it is found that the VSM system appears to have comparable performance and support to the system from the perspective of fault ride through (FRT), provision of inertial response and reaction to voltage steps. However, while VSM can potentially provide a fast fault current injection through the implementation of appropriate control, a key limitation is on the magnitude of fault currents, so it is unlikely to be capable of offering the same level of support compared with SCs and SGs.

1 Introduction

The operation of conventional power systems largely relies on the inherent properties of synchronous generators (SGs), which provide inertia, damping and fault current capacity to facilitate the system's protection and control. In recent decades, there has been a significant increase in renewable generation replacing conventional SGs and this trend is expected to continue in the coming years [1]. Typically, renewable sources require power electronics-based converters to interface with the AC power networks. The dynamic behaviour of these types of power electronics devices is very different from conventional SGs and is largely dependent upon their controllers [2]. One of the most typical control strategies for converter-based resources is to provide constant power to the grid, which does not naturally provide inertia and frequency support to the system. Furthermore, due to the constraint of current capacity, their capability in providing fault currents is very limited [3], [4]. As a result, the overall short circuit level (SCL) and inertia of the system are decreasing dramatically and the system strength is becoming progressively weaker with the rapid increase of non-synchronous generation. In the GB power system, it is anticipated that by 2025, the inertia level can decrease by 40% [5] and the minimum SCL in some regions can decrease by over 80% [6]. In addition to fault level and inertia contribution, the capability of converters to remain connected to the system during severe faults or other disturbances and their general responses to such events need to be fully understood and evaluated for reliable operation of future power system dominated by converters.

To address the aforementioned operational challenges caused by the increasing penetration of converter-interfaced generation, two key approaches are being widely investigated: one is to install synchronous condensers (SCs) to mitigate the effect of decommissioned SGs; and the other is to investigate how the converters could be controlled to provide valuable properties, e.g. inertial response, fast frequency regulation and fault current injection to better support the system operation.

SC is a type of synchronous machine without a prime mover, so it does not provide any sustained active power to the network but can supply and absorb (if necessary) essential reactive power to/from the system to stabilise the grid voltage. Therefore, SCs are conventionally mainly used for power factor correction and voltage regulation via injecting/absorbing reactive power [7]. Due to the similar inherent behaviour as SGs, SCs are considered to have a critical role in supporting the operation of systems dominated by converters [8], [9]. SC is a very mature solution widely used in power systems worldwide and in recent years, there has been an increasing trend of using this technology to solve the challenges in weak power systems, e.g. countries like the UK, Denmark and USA have all deployed SCs in their network in recent years to support the integration of renewable resources [10]–[12]. A major positive aspect of the SC is that, unlike converters, its inertial and fault current support to the system are inherent, so it does not require dedicated measurements to provide such services. Therefore, this solution is particularly valuable for maintaining the system inertia level, thus avoiding the mal-operation of RoCoF-based Loss of Main (LoM) relays (particular those set with zero-time delay) since there is no measurement delay in this solution. Furthermore, it may be

possible to reuse the decommissioned SGs by converting them into SC, since the implementation of both machines is very similar. In the GB transmission system, as part of the stability path-finder initiative raised by the transmission system operator [13], inertia has been considered as a service provided to the system and some in-service SGs start to be run as SCs in certain periods (e.g. Cruachan power station) to provide inertia and fault current support to the system [14]. However, inertia in the SC can be relatively small, with typical inertia constant of around 2-3 s [15]. In order to fully compensate for the effect of huge amounts of decommissioned SGs, potentially there is a need for significant newly-installed or converted SCs to be online.

Another approach being widely investigated is to control the converters to provide properties that could be offered by SGs. The key benefit of this approach is that there will be a significant increase of converter capacity in the system anyway and new control could be deployed in newly installed units and also potentially via updating the software/firmware of installed systems. Extensive research has been reported in the literature, investigating different types of control techniques for converters to provide grid support with frequency regulation [16], [17], inertial response [18]–[21] and power system damping [22], [23]. Reference [24] presented power synchronisation control to enable converters to provide power and voltage support to a weak grid. Reference [25] suggests the concept of a virtual synchronous machine (VSM), which aims at imitating the behaviour of SGs via the deployment of specifically designed controllers on converters. VSM is a type of grid forming converter and if implemented properly, it can maintain voltage and frequency of the grid in a similar manner like a SG. In the literature, there are different types of implementations of VSM [26]–[28]. Through the provision of emulated inertia from VSMs, it is expected that by 2025 GB's power system's inertia can be improved from 115 GVAs to an equivalent inertia level of 175 GVAs and it is possible to further achieve an equivalent inertial level of 270 GVAs (which is approximately the maximum inertia level in today's GB system) [29].

Despite extensive work has been conducted in the development of VSMs, there are no comprehensive studies for evaluating dynamic behaviours of VSMs under different grid events and comparing their capabilities against SCs and SGs. Therefore, in this paper, simulation studies are presented to evaluate and compare the dynamic behaviour and capability of a representative VSM model (validated against a prototype battery-driven VSM system) with SC and SG, under a wide range of system conditions, including frequency disturbances, voltage depressions and short circuit faults. The study cases are selected based on some of the technical criteria specified for the stability pathfinder service required by National Grid ESO [13]. The studies aim to offer insights on the level of support VSM could offer to the system as compared with SC and SG, and their advantages, potential issues and limitations that need to be considered for a wider application in the system.

The rest of the paper is organised as follows: Section 2 provides an overview of the technical specifications that are required from the SG, SC and VSM while connected to the

network. Section 3 presents the simulation models of SG, SC VSM and distribution network that is used for the analysis. Case studies and the analysis of the dynamic performance of VSMs as compared with SCs and SGs is presented in Section 4 and finally, Section 5 concludes the paper with some future work.

2 Technical Criteria for Evaluating VSM, SC and SG

This section presents a number of technical criteria that have been selected for evaluating the dynamic performance and capability of VSMs as compared with SCs and SGs. The criteria have been selected based on the technical performance requirements as specified by the Stability Pathfinder, which is an approach initiated by National Grid ESO to seek potential solutions that could support the stable operation of the future system with increasing renewable penetration [13]. This paper focuses on the following aspects: 1) short circuit faults; 2) fault ride through capability; 3) inertia response during severe frequency deviations; and 4) voltage depression events, as described in detail in the following subsections.

2.1 Short circuit faults

With a decrease in SGs in the power system, the SCL is also decreasing and it could compromise both the stability of converters and the reliability of the protection systems. As reported in [30], when the SCL decreases to a certain level, the Phase-Locked Loop, which is widely used by converter control systems could start to experience stability issues, thus resulting in overall instability of converters. For the protection system, conventional overcurrent protection relies on sufficient fault current to detect faults and react within the required time. Based on [3], the performance of the overcurrent relay with a large proportion of inverter-based generation in the distribution network was analysed, and it was found that if no action is taken against the decreased fault level, new protection schemes are required to replace existing overcurrent protection to ensure the effective protection of distribution network. Furthermore, based on [31], the fault characteristics will have an impact on distance protection performance, and the fault characteristic of converters are dominated by their controllers. Therefore, it is critical to assess the short circuit contribution and the fault characteristics of VSMs during short circuit events as compared with SCs and SGs.

2.2 Fault ride through (FRT)

For any solution aimed to provide support to the grid, the capability to remain connected to the system in order to provide the expected voltage support is crucial. Based on the grid code [32], the solutions must ride through a voltage depression to the level of 0.3 pu with a duration of 140 ms. Therefore, a voltage profile matching the FRT requirements for power park modules as specified in the grid code was simulated to evaluate the VSMs' FRT capability and same voltage profile is utilised to compare the performance with SCs and SGs although the FRT requirement for synchronous power generation module is different.

2.3 Inertial response support

With decreased system inertia, the frequency will deviate faster with a higher RoCoF for the same power imbalance. If

there is a loss of generation due to unexpected events, frequency drop from the steady-state (operational range is 49.8 to 50.2 Hz) takes place. Reference [33] suggests that, in the future, primary response from the SG will become inadequate and expensive. Furthermore, it is expected that in the future, due to low inertia, the RoCoF based LOM protection can be at risk of unnecessary tripping of the connected generators [34]. Hence, in this paper, a frequency ramp with a constant RoCoF is used to evaluate the inertia behaviour of both SC and VSM. Furthermore, the frequency ramp has been specifically chosen based on [13] to have a frequency range between 47Hz to 52 Hz with a RoCoF of 1 Hz/s to evaluate the provision of inertia response and the capability to remain connected to the system over a wide range of frequency and high value of RoCoF.

2.4 Reactive power to support voltage regulation

This item will evaluate the capability of VSM as compared with SC and SG to provide reactive power support to the grid when a voltage disturbance occurs. It is expected from the solutions to remain connected under $\pm 10\%$ voltage regulation while providing reactive power support to the grid.

3 Simulation Models and Setup

To analyse the dynamic behaviour of three types of machines-SG, SC and VSM, a simplified distribution network model, as shown in Fig. 1, has been used. The electrical parameters of the three types of generators have been set to be the same or equivalent to each other so that a fair comparison of the performance can be drawn. Necessary values of the different parameters of the distribution network model, SG, SC and VSM are presented in Table 1.

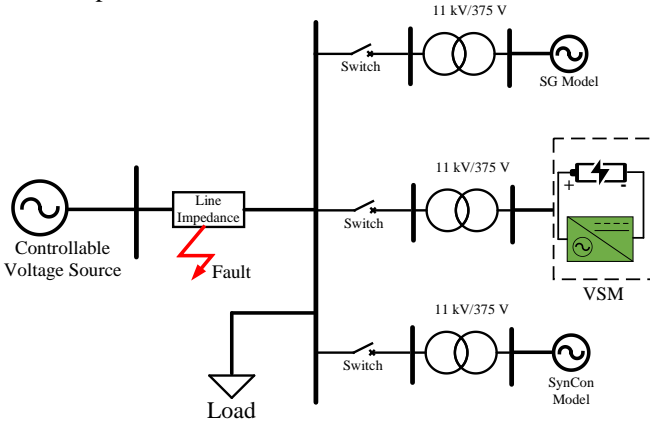


Fig. 1. Simulation setup

3.1 Modelling of the SG

The dynamic construction of the SG is well studied and available in the literature [35]. The block diagram of the implemented SG for the analysis in this paper is shown in Fig. 2. There are two main controllers used for the SG, i.e. the exciter for field windings that can maintain stable voltage, and the governor to for regulating active power. For the excitation system, the model from [36] is used in this work, and for the governor, the GAST model [37] representing gas turbine dynamics is used. Since the main interest of the study is on inertial response and the droop control is not applicable for SC, the droop in the SG's governor has been disabled, where the similar setup was also adopted for VSM.

Table 1 Simulation parameters

Simulation Parameters	Description and value
Frequency	$f_0 = 50$ Hz
Grid Voltage	$V_{grid} = 33$ kV
Line Impedance	$Z_{line} = 0.5765 + 1.7 \Omega$
Rated Power	$S_{rated} = 246.817$ kVA (for all three machines)
Reference Power	$P_{ref} = 100$ kW (for SG and VSM) and $P_{ref} = 0$ kW (for SC)
Inertia constant	$H = 2$ s (for all three machines)
Damping	$D = 1$ (for all three machines)
Load	$P_{Load} = 10$ kW

3.2 Modelling of the SC

As mentioned before in the paper, SC is a special type of SG without the prime mover. SC cannot provide sustained active power to the system, so there is no governor available for SC. In this paper, implementation of SC is similar to the SG as presented in Fig. 2 with the same excitation system, but in this case, there is no governor, and mechanical power fed to the SC is zero.

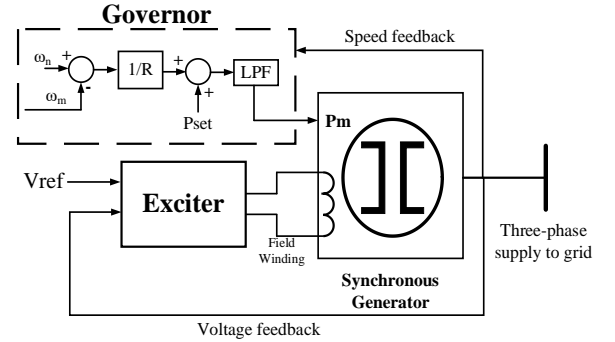


Fig. 2. Schematic of the SG model

3.1 Modelling of the VSM

The subject of VSM has been widely investigated so there are different ways of implementing the VSM. In this paper, a model of VSM provided by an industrial partner has been used for the study. For confidentiality reasons, the detailed implementation was not made available but a generic diagram of the VSM can be represented by Fig. 3. The VSM model is designed for a battery system and has been validated against a physical battery VSM prototype system, so its performance is realistic against the physical prototype system. The VSM has both current and voltage control, and virtual inertia, damping and droop can be achieved by the separate outer control loop.

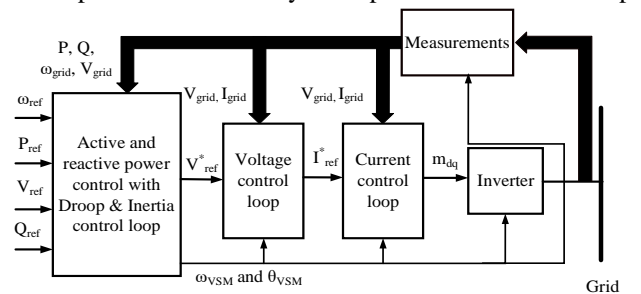


Fig. 3. The generic control diagram of VSM

4 Case studies

5.1 Studies of short circuit faults

In this study, two types of fault cases are simulated, i.e. (1) a three-phase and (2) a single-phase to ground fault scenarios, to evaluate the capability of VSM, SC and SG in providing fault current contribution and their fault current characteristics. The fault is located between the controlled voltage source and the tested models as shown in Fig. 1. The fault impedance is assumed as 1Ω , and the fault duration is 1 s, starting at 5 s. As shown in Fig. 4, the voltages (for all three-phases) are severely depressed during the three-phase fault as expected. The three-phase instantaneous currents for all three units are shown in Fig. 4. Similarly, the instantaneous voltages and currents for the single-phase to ground fault are shown in Fig. 5.

It can be observed in Fig. 4 and Fig. 5, that the fault currents from SG and SC have similar characteristics and magnitudes (over 10 pu), which are much higher than VSM. This is due to their strong overloading capability. In the case of VSM, a fast reaction to fault is observed with fault current injection within 2 cycles. At the beginning of the fault, the current waveforms were distorted and the current magnitude is limited (approximately 2 pu). According to the technical criteria, both SC and VSM fulfil the conditions of fast current injection [13]. However current magnitude from VSM during fault is limited (compare to SG and SC) due to the physical thermal limit of power electronics components.

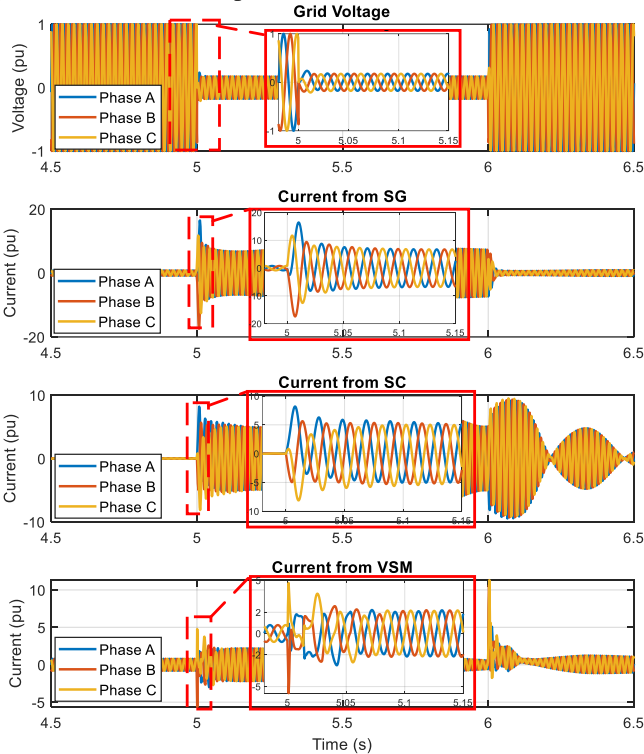


Fig. 4. Grid voltage and currents during the three-phase fault

5.2 FRT

The FRT voltage profile for power park modules according to the GB's grid code is shown in Fig. 6, which is applied at the controllable voltage source as shown in Fig. 1 for emulating a severe fault event. The RMS current and reactive power outputs of the VSM, SC and SG are also shown in Fig. 6. From

the figures, it can be observed that the VSM successfully rides through the fault as the SG and SC. The behaviour of both SG and SC are almost similar with a large amount of current and reactive power injected to the system due to their large overloading capability. While the VSM does not appear to inject the same level of reactive power as the SC and SG can provide, its performance appears to satisfy the grid code requirements, which require the injection of reactive current into a restrained voltage depression at the point of connection within 5 ms of the event.

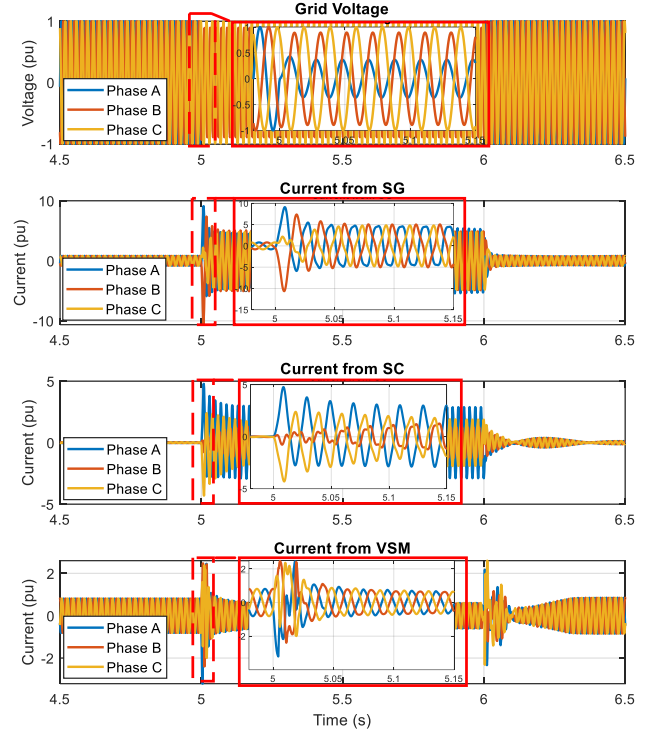


Fig. 5. Grid voltage and currents during the single-phase fault

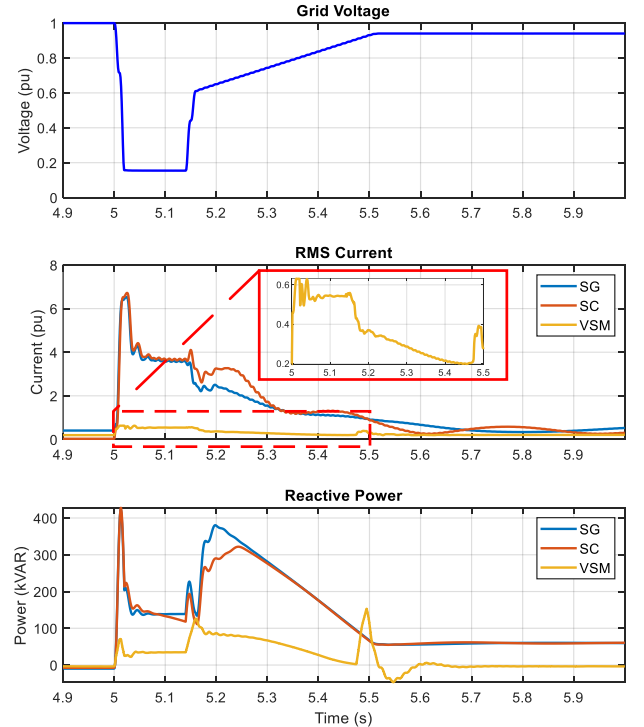


Fig. 6. Simulation results for FRT

5.3 Studies of inertial response support

In this section, two frequency ramps with a RoCoF magnitude of 1 Hz/s are simulated, where the positive ramp lasts for 2 s and the negative ramp lasts for 5 s as shown in the first graph of Fig. 7. Three different technical criteria are investigated through this simulation: (i) inertial response support provided by all three units (ii) capability to stay connected in providing inertia response over the frequency range of 47 – 52 Hz and (iii) capability in withstanding a RoCoF of 1Hz/s. It can be observed from Fig. 7 that all three conditions are met by the units. In case of inertial support, inertia constant for all three units is set as $H = 2 \text{ s}$ (can be seen from Table 1) and for SC and SG, the inertia response is supported by calculated value as calculated through (1), e.g. for the second ramp, expected power change is 20 kW for both SC and SG.

$$\Delta P = - \frac{2 \times H \times S_{rated} \times RoCoF}{f_o} \quad (1)$$

However, inertia behaviour of VSM is slightly different, it is providing a higher power change initially and then decreasing with time for the frequency ramp. The comparison between actual and estimated power changes are presented in Table 2. Two possible reasons can be identified for this unusual behaviour of VSM compared with SG and SC.

- The actual rated power used in the control loop of the VSM unit is different from the claimed capacity. This could be a base power error in the model provided by the industrial partner and can be resolved by the model supplier by confirming the consistency of the base power.
- The VSM model may have additional control loops which is different from the model shown in Fig. 3. Thus, VSM unit is injecting additional power initially and slow decrease of the power overtime to ensure overall stability of the system. However, further works need to be carried out to identify more accurate ways of establishing equivalent inertia and damping parameters of VSM solutions.

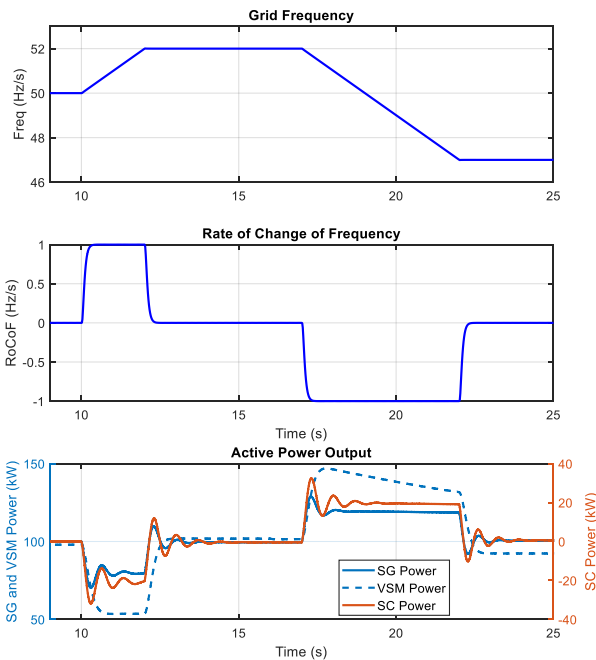


Fig. 7. Simulation results for inertial response

Table 2 Comparison of actual and estimated power change due to frequency ramp

Solutions	H (s)	S_{rated} (kVA)	$RoCoF$ (Hz/s)	f_o (Hz)	ΔP_{est} (kW)	ΔP_{act} (kW)	Error (%)
SG	2	246.817	-1	50	19.75	20	1.25
SC						20	1.25
VSM						38	48

5.4 Voltage step

According to the grid code, the solution should remain connected throughout the 10% voltage depression and provide reactive power support to the grid. Therefore, a simulation with 10% voltage depression has been carried out and results are shown in Fig. 8. The second and third graphs of Fig. 8 are showing the RMS current and reactive power provided by VSM, SC and SG, respectively. As can be seen in Fig. 8 the reactive power support from both SC and SG is almost the same while VSM support is limited. However, the units remain connected throughout the event and satisfy the grid requirement.

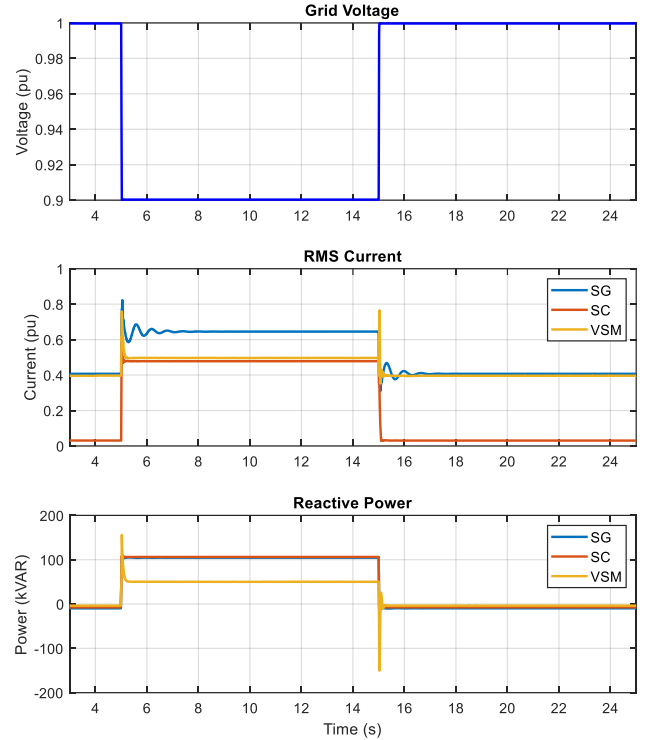


Fig. 8. Grid voltage during voltage step simulation

6 Conclusions and Future Work

In this paper, a wide range of simulations has been carried out to evaluate and compare the dynamic behaviour of the SG, SC and VSM. It can be observed that the behaviour of both SG and SC very almost similar for all studied cases. It was also found that the VSM system appears to have comparable performance and support to the system from the perspective of fault ride through, provision of inertial response and reaction to voltage steps. However, for short circuit faults, while VSM can potentially provide a fast fault current injection, a key limitation is on the magnitude of fault currents, so it is unlikely to be capable of offer the same level of support compared to SCs and SGs. Future work will focus on simulation of more

complex cases, including wider network models, to further evaluate the capability of VSMS to support the operation of future grids. The physical tests of the prototype VSM systems to validate the findings from the simulation studies will also be conducted.

7 References

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