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Novel Virtual Synchronous Generation Control with Virtual Impedance[#]

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ABSTRACT

In recent years, the power industry has seen a significant uptick in renewable energy integration, including solar and wind farms, accompanied by energy storage systems. While this has increased overall generation capacity, it has also posed challenges to grid security and vulnerability. Key issues such as low short circuit ratios due to renewable integration and the retirement of synchronous machines have weakened grids. Grid forming inverters therefore have emerged as a vital solution, aiding solar and wind farms in maintaining stability during low short circuit ratio conditions. However, traditional Virtual Synchronous Generation (VSG) controllers, while beneficial, often introduce oscillations during disturbances, threatening network stability. This paper introduces an innovative approach that integrates Virtual Synchronous Generation Control with a Virtual Impedance Strategy to address stability challenges in solar and wind farms under low short circuit ratio conditions. By eliminating the need for Phase-Locked Loops (PLL), this method effectively mitigates oscillations during faults and voltage disturbances, thereby ensuring grid stability, with compliance to grid codes such as those of NER and AEMO Australia serving as guidelines. Implementation in PSCAD, which is widely used in the power system industry, validates its capability to meet stringent grid code requirements.

Keywords: Grid forming inverter (GFM), grid integration of renewable energy, virtual synchronous generator (VSG), weak grid, virtual impedance.

1. INTRODUCTION

Due to high penetration of renewable energy resources into modern power systems with voltage source converters, inter-actions between AC grids and converters have become a major concern. Various researchers have highlighted 'Short Circuit Ratio (SCR)' as an indication of the strength of a grid [1-4]. A grid is considered 'weak' and 'very weak' for SCR<3 and SCR-1, respectively [5-6]. In the recent system strength requirements report by Australian Energy Market Operator (AEMO), tripping of transmission line after fault has been identified as an essential factor for weakening strength of a grid [7]. While the VSCs have been highlighted as an attractive solution [8], the presence of power electronic equipment in weak grids affects the terminal voltage of the system making it more sensitive [9]. Integration of renewable energy resources into the weaker grid brings further challenges into the system due to their intermittent behavior. Lack of interactions between VSCs and weak grid raises concerns about achieving a stable and reliable system [10]. The major reasons for unstable issues due to lack of interactions between VSCs and weak grids are-1) phase angle difference between converter side voltage and grid side voltage 2) frequency oscillation by phase-locked-loop (PLL) during disturbances 3) higher impedance of weaker grid. A supplementary frequency-based control loop to provide damping for oscillations has been proposed in [11]; however, interaction between converter control and grid dynamics is reported as an issue for unstable behavior for power reaching a certain value [12-13]. A novel approach to inverter impedance-phase compensation method was proposed in [14-15]. A novel virtual synchronous generation control with grid synchronization has been proposed in [16-17]. The solutions provide various insights on ad-dressing challenges; however, to authors' best knowledge, further investigation is required on very weak grid-based VSCs on the interactions between converter and grid side voltages.

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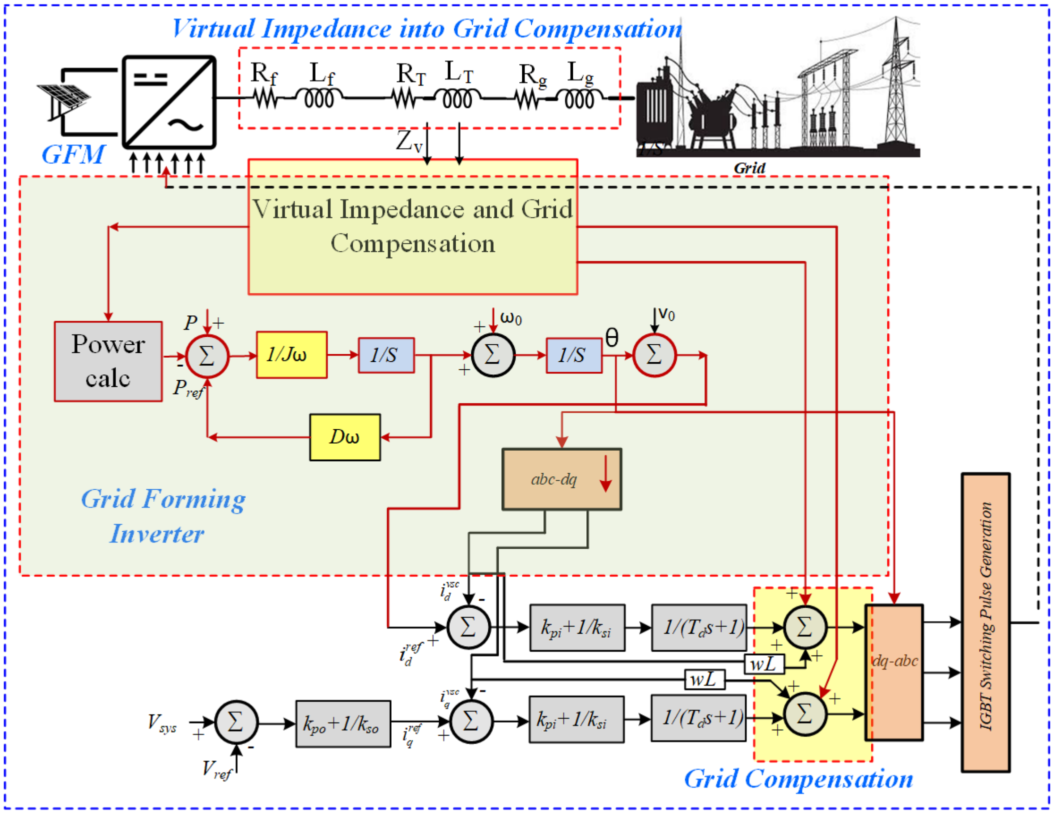

Fig. 1 Proposed VSG Control of GFM

In recent years, power industries have witnessed a shift towards the need for grid forming inverters to tackle the challenges in weak grid integration of renewables. Grid forming inverters are a widely used solution in both industry and research in this aspect, which can help these solar and wind farms to operate in stable manner during low SCR conditions. Traditional VSG controllers can assist in such low SCR; however, it associates oscillations during disturbances which can pose threat to the network. In the context of weak grids, one significant challenge for grid forming inverter is the accurate emulation of inertia in low short circuit ratio conditions as during transient conditions grid's ability to support might be compromised. Furthermore, in weak grid, while mimicking synchronous generator, a rapid change in voltage or frequency may cause unstable behavior in the system. Furthermore, interactions between controllers are another factor determining the performance during transient conditions.

Hence, in this paper a novel virtual synchronous generation control integrated with virtual impedance strategy for grid voltage drop compensation across the line and angle compensation on the inner controller has been proposed. The virtual impedance control has been designed based on the line impedance and grid impedance and transformed into voltages in dq transformation. Angle compensation is generated from the dq transformed voltage and both are compensated into the inner current control loop. The virtual synchronous generation participates in the outer control operation by generating angle for the dq transformation, which eliminates the necessity of PLL. This means the grid forming inverter operates without any PLL can help inverter low SCR avoid oscillations during voltage and angle shift disturbances. Moreover, the ability of this control method to dynamically adjust makes it applicable to a wide range of network conditions. This adaptability ensures that the controller can meet grid code requirements across different network topologies and strengths, enhancing the robustness and flexibility of VSGs in various power system scenarios. The controller has been implemented in PSCAD and it has been observed that the controller can meet grid codes requirement for weak grids.

2. PROPOSED VIRTUAL SYNCHRONOUS GENERATOR CONTROL

Fig. 1 depicts a one-line diagram of the system along with the proposed control method. The system is composed of a VSC station connected to the host AC system through an LR filter and transmission line. The filter is represented by Rf & Lf; transmission line is represented by RT & LT and grid impedance is represented by Lg & Rg. In the proposed control, virtual synchronous generation control has been applied by adopting well-known swing equation of synchronous generator as show below.

$$J_{vsg}\frac{d\omega}{dt} = P_{ref} - P - D(\omega - \omega_0)$$

Where, P is actual active power delivered by the inverter, P_{ref} is reference active power, D is virtual moment of inertia, ω is virtual angular velocity, and ω_0 is grid frequency. The VSG control is implemented on outer loop and it is free of PLL as it can generate rotational angle for the abc to dq and vice-versa transformation. The grid compensation of voltage and angle has been implemented based on the virtual impedance across transmission line and grid impedance, which is fed into the inner current control.

Transformed voltage for the inner loop can be represented with below expression which has been modeled from the virtual impedance.

$$u_{a_{syn}} = \frac{u_{2a}Z_T arc\tan(z_T) + (u_{2a} - u_{1a})Z_g arc\tan(z_g)}{Z_T arc\tan(z_f)}$$

Where, ZT and Zg are the line and grid side impedance.

To understand how the voltage expression shown above mimics the grid voltage and phase angle compensation, the formulation of dq transformed voltage for a classic vector is expressed as.

$$u_d = \frac{2}{3}\left\{u_a\cos(\omega t) + u_b\cos\left(\omega t - \frac{2\pi}{3}\right) + u_c\cos\left(\omega t + \frac{2\pi}{3}\right)\right\}$$

Based on the above-mentioned expression, modified d-axis voltage for the proposed method can be derived below

$$u_d^{dyn} = \frac{1}{3}\begin{bmatrix} \{u_{2a} + \Delta u_{fa}Z_t\}\{e^{j\omega t} + e^{-j\omega t}\} + \\ \{u_{2b} + \Delta u_{fb}Z_t\}\left\{e^{j\left(\omega t - \frac{2\pi}{3}\right)} + e^{-j\left(\omega t - \frac{2\pi}{3}\right)}\right\} + \\ \{u_{2c} + \Delta u_{fc}Z_t\}\left\{e^{j\left(\omega t + \frac{2\pi}{3}\right)} + e^{-j\left(\omega t + \frac{2\pi}{3}\right)}\right\} \end{bmatrix}$$

$$\cos\theta = \frac{1}{2}\left(e^{j\theta} + e^{-j\theta}\right); \sin\theta = \frac{1}{2}\left(e^{j\theta} + e^{-j\theta}\right)$$

;

$$\arctan(z_g) = \frac{j}{2}\ln\left(\frac{j + z_g}{j - z_g}\right); Z_t = \frac{Z_g\ln\left(\frac{j + z_g}{j - z_g}\right)}{Z_f\ln\left(\frac{j + z_f}{j - z_f}\right)}$$

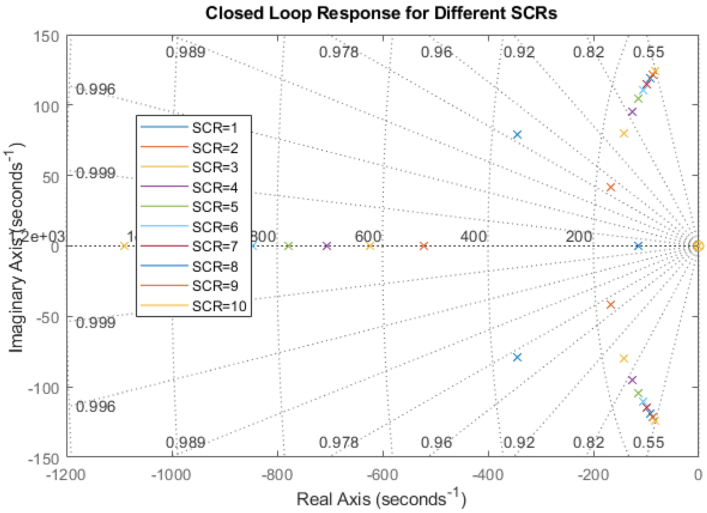

Fig. 2 Performance comparison during 3LG fault at 4sec at SCR 1.5

Furthermore, the current control is also updated with the same expression. Through this modification, the current controller adjusts its references with higher stable margin as the d-axis voltage u_d^{dyn} equipped with grid dynamics. The q-axis voltage u_q^{dyn} is also formulated below as

$$u_q^{dyn} = -\frac{1}{3j}\begin{bmatrix} \{u_{2a} + \Delta u_{fa}Z_t\}\{e^{j\omega t} - e^{-j\omega t}\} + \\ \{u_{2b} + \Delta u_{fb}Z_t\}\left\{e^{j\left(\omega t - \frac{2\pi}{3}\right)} - e^{-j\left(\omega t - \frac{2\pi}{3}\right)}\right\} + \\ \{u_{2c} + \Delta u_{fc}Z_t\}\left\{e^{j\left(\omega t + \frac{2\pi}{3}\right)} - e^{-j\left(\omega t + \frac{2\pi}{3}\right)}\right\} \end{bmatrix}$$

For stability analysis, the transfer function of the current open-loop, $G_{i_{ol}}(s)$ is calculated through below expression.

$$G_{i_{ol}}(s) = G_i(s) * G_d(s) * G_p(s) * G_{vsg}(s) * G_{plant}(s)$$

Where, $G_i(s)$ is the transfer function of the inner loop PI controller, $G_d(s)$ indicates time delay, $G_p(s)$ relates to the pulse width modulation, $G_{vsg}(s)$ relates to the proposed VSG, and $G_{plant}(s)$ is the plant filter. Pole zero mapping of the controller has been demonstrated in Fig. 2. The closed loop transfer function of inner current control is expressed below where Kc is the closed loop gain.

$$G_{i_{cl}}(s) = \frac{G_{i_{ol}}(s)}{\left(1 + K_c G_{i_{ol}}(s)\right)}$$

3. TIME DOMAIN SIMULATIONS & STABILITY ANALYSIS

The performance of the proposed controller has been tested in PSCAD/EMTDC power system software widely used in the power system industry for grid integration.

In Fig. 3, comparison between proposed VSG, a conventional VSG and conventional PQ control has been presented, where 3LG fault applied at 4sec with 430ms duration for SCR 1.5. Please note SCR 1.5 is a very slow SCR, and it can be observed from Fig. 3, that the proposed controller can withstand the fault and recover smoothly. PQ controllers clearly cannot withstand such low SCR and traditional VSG controllers can with stand the fault however it takes time to recover as a result of high rise time. A similar case study with SCR 2.4 has been presented in Fig. 4. Authors have shown SCR 2.4 as PQ control can run at SCR 2.4 with best tuning and iq injection, however, recovery performance is always worse than VSG control.

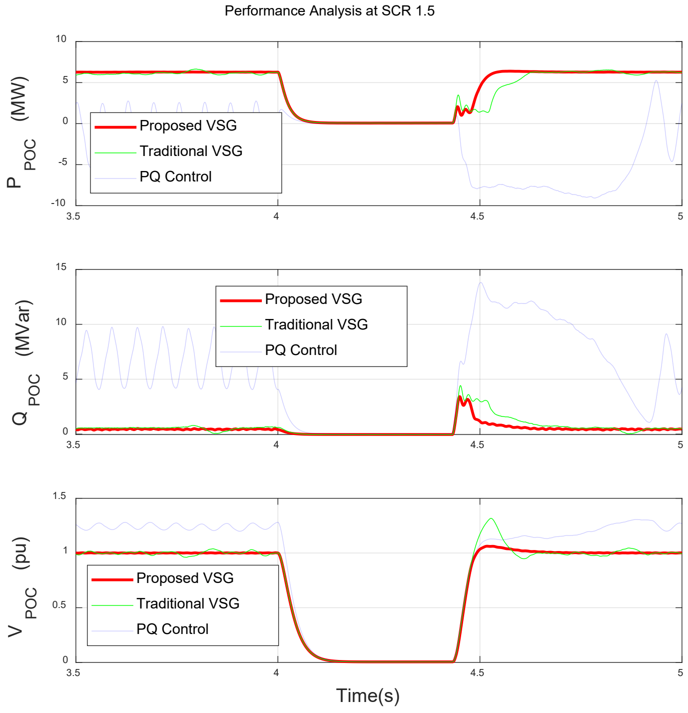

Fig. 3 Performance comparison during 3LG fault at 4sec at SCR 1.5

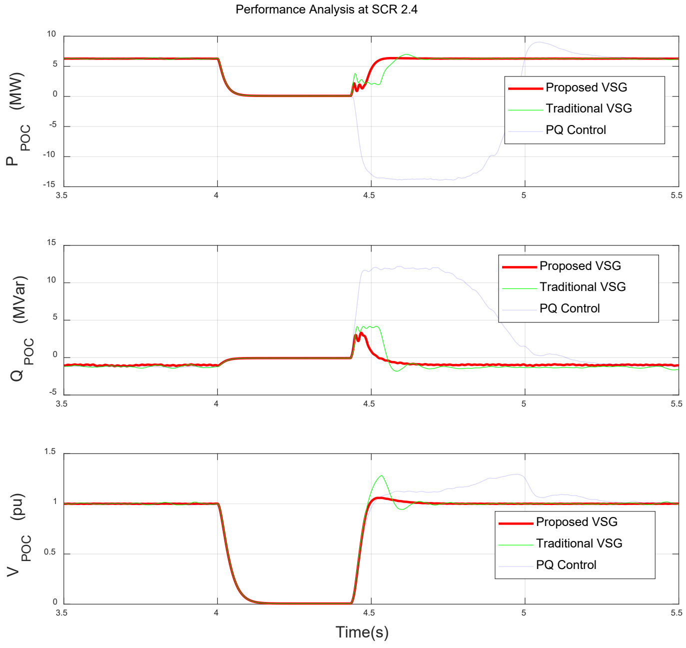

Fig. 4 Performance comparison during 3LG fault at 4sec at SCR 2.4

To highlight the benefits of of proposed controller over traditional VSG, another case study has been presented in Fig.5, where SCR and active power reference has been changed. SCR has been changed from 5 to 1.5 meaning a shift from strong grid to weak grid.

The active power reference has been changed from 0.9 pu to 0.2 pu. It can be observed that during SCR change, proposed controller due to the virtual grid impedance technique with VSG provides a grid voltage and angle compensation, which smoothens the transition. However, traditional VSG controller experiences stiffness during the transition. It can however recover due to the virtual synchronous generator controller, but clearly highlights the major improvement by the proposed controller.

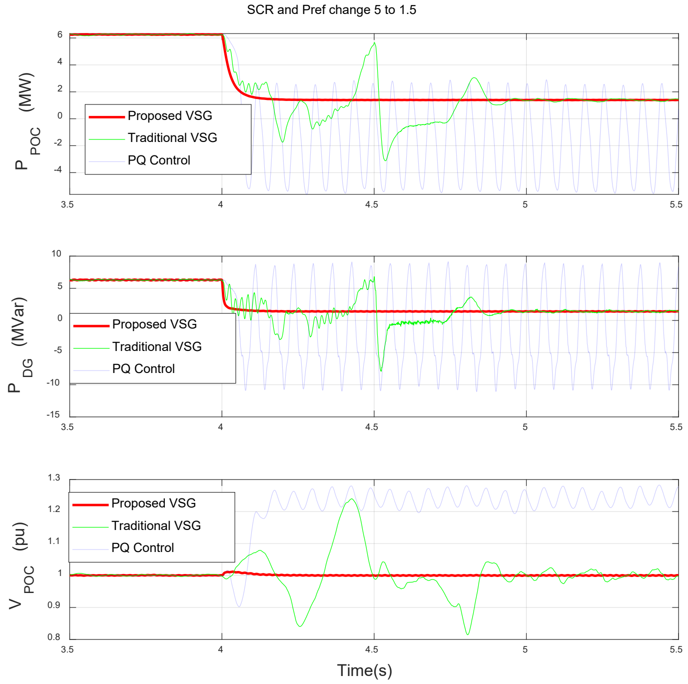

Fig. 5 Performance comparison during Pref change with SCR varying from 5 to 1.5

4. CONCLUSIONS

This paper addresses the challenges posed by weak grids in the context of increasing renewable energy integration. Weak grids, characterized by low short circuit ratios and the retirement of synchronous machines, present significant hurdles to grid stability. To tackle these challenges, the paper introduces a novel approach: Virtual Synchronous Generation Control integrated with a Virtual Impedance Strategy. This innovative method aims to stabilize solar and wind farms by mitigating oscillations during disturbances, thus ensuring grid stability. Unlike traditional Virtual Synchronous Generation (VSG) controllers, this approach eliminates the need for Phase-Locked Loops (PLL), enhancing system reliability. 3LG fault tests with 430ms duration for different methods depict the performance improvement of the proposed controller. Furthermore, SCR change from strong to weak grid demonstrates a network operating condition that can happen in network with many renewable generations. The tests verify the performance of the proposed control strategy. Stability results from small signal modeling perspective will be further provided in full paper. Compliance with grid codes, such as those of NER and AEMO Australia, serves as a guideline throughout the development process. Implementation and evaluation in PSCAD validate the effectiveness of the proposed approach in meeting stringent grid code requirements.

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