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Research Article

Synchronization Capability and Frequency stability Improvement of PLL based GFLI using E-PIRC Connected to Weak and Distorted Grid

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Abstract— Voltage source converter-based phase locked loop (PLL) grid following inverters (GFLI) are one of the technologies used in inverter-based resources (IBR) for integration of clean and renewable energy to an energized grid. However, PLL-based GFLI have drawback of synchronization instabilities when connected to an energized weak grid or a grid low short circuit ratio (SCR). The factor responsible for the synchronization difficulties which results to frequency instability is due to vector current control (VCC) loop interaction between the current controller PLL dynamics. The traditional PIRC (T-PIRC) harmonics compensation and disturbance rejection capability in the VCC deteriorates under weak grid, thus resulting in cascading effect on PLL dynamics. To improve the synchronization capability, a voltage feedforward control is proposed and enclosed within the T-PIRC, the enhanced PIRC (E-PIRC) is able to reject the disturbance under varying SCR conditions. Simulation results using MATLAB/Simulink shows the frequency stability and synchronization capability is improved under varying SCR conditions. Conclusively, the proposed method is robust in terms of grid weakness and its implementation does not require additional controller.

Keywords— IBR, Weak grid, GFLI, PLL, T-PIRC, E-PIRC, voltage disturbance

1. Introduction

Integrating renewable energy sources or resources (RES/RERs), like solar and wind power, into the electrical grid has gained substantial attention in recent years due to environmental concerns of conventional power generation sources; and the growing need for clean and sustainable energy solutions [1-4]. The term wind and solar farm are mainly referred to as inverter-based resources (IBRs) [5]. Inverter Base Resources (IBRs) technology plays an important role in converting the RES into AC power using power electronics converter technology, which is finally injected into the utility grid [6]. Some merits associated IBRs include high reliability, high energy conversion efficiency, fast dynamic response and flexibility as compared with conventional generators. [7]. At high penetration level of grid-connected inverters poses some challenges such as power quality, stability and grid synchronization issues. [8].

The RERs for IBR are mostly located in remote areas, therefore long transmission distance is required to transfer the converted power; thus, leading to increase in the line impedance due to long distances and increase in the number of converters, that could lead to weak grid scenarios due to high impedance leading to low X/R ratio and a low short circuit ratio (SCR) [9 -10]. The SCR is widely used index in IBR technology to quantify the weakness or strength of a power system. For instance, grids with SCRs of greater than three are classified as strong ones, while SCRs below two are classified as a very weak network [12].

The power electronics converters employed in IBRs to convert the renewable energy resources into electrical power are mostly classified as into two main groups, mostly based on their synchronization capabilities: 1) grid-following inverters (GFLIs) and 2) grid-forming inverters (GFMIs). Synchronization is the technique employed to connect either or all of the inverters to an energized electrical grid. For the research work, our task is focus on GFLI, and it is a phase locked loop (PLL) base voltage source converter (VSC) which operates as controllable current sources to deliver the desired value of active and reactive power to an energized grid [13]. Under weak grid scenario, GFLI faces synchronization difficulties due to control interactions of current control loops and the dynamics of the PLL, therefore leading to voltage and frequency stability issues.

Vector control or vector current control (VCC) is mostly used as inner loop control for PLL-based GFLI system for control and regulation (voltage and frequency) [14], the control uses mostly uses the stationary frame or dq control, because of its simplicity and flexibility [14]. Among the controllers or regulators used for VCC includes linear controllers such proportional integral (PI) controllers, and non-linear controllers such as the traditional proportional-integral repetitive controllers (T-PIRC). For instance, PI controllers' gains depend on the line parameter, as the weakness of the line increased the synchronization effort of GFLI deteriorates leading to instability [14]. As for the T-PIRC, it is a controller designed for periodic disturbance rejection of harmonics and its model the fundamental frequency of the GFLI [15-18]. However, under weak grid condition or low SCR, the voltage disturbance leads to poor harmonics compensation by the T-PIRC leading to surge of harmonics in the VCC control, and the interaction between the VCC and the PLL dynamics leads to poor synchronization, which leads to frequency instability. To mitigate the issue of voltage disturbance, and to enhanced the synchronization without much changes or need of retrofitting of electronics component of the VCC and PLL, a voltage feed forward is proposed within the traditional PIRC (T-PIRC) to improve the overall GFLI system stability by enhancing the synchronization capability of the GFLI.

2. Related Work

The work in [19] introduced a novel fractional-order repetitive controller (NFO-RC) for grid-connected inverters under weak grid scenario. This improved proportional-integral multi resonance repetitive controller (PIMR-RC) effectively tracks the load current signals without steady-state error. Utilizing a fractional delay (FD) filter, this controller attains frequency adaptability using a simplified Thiran formula [19], reducing real-time computational load. While proving better performance than existing controllers, this study lacks consideration for diverse grid conditions and load types.

The research in [20] presented a proportional-integral multi-resonance (PIMR) repetitive controller for grid-tied inverters. Demonstrating zero steady-state error in tracking reference current signals, this controller outperforms existing models [20]. Offering insights into parameter impacts and selection guidelines, this paper introduces a promising solution for grid-tied inverters, yet it focuses solely on a specific controller type without broader comparisons or metrics like cost and complexity.

The work in [21] proposed a new design for a higher-order repetitive controller that uses a phase lead compensator to improve the performance of the control system. The research compares the performance indices of the proposed controller with that of a conventional repetitive controller under frequency variations, results via simulation shows that the proposed controller outperforms the conventional controller [21]. However, the proposed controller is designed specifically for repetitive current control of a two-level grid connected inverter. Therefore, the applicability of the proposed controller to other multilevel inverter systems may be limited.

Furthermore, the work in [22] studied and investigates grid impedance variations, switching frequencies, and PV output voltage variations of grid-connected inverters, based on the H-infinity control scheme. The authors proposed a control scheme using a game theory algorithm for the H-infinity to determine the weighting function of the current control loop of the system and compared the performance of the proposed control scheme with PI control [22]. Simulation results shows that with the proposed scheme has low THD index as compared with conventional PI scheme. However, – H infinity controllers have a computational burden with fixed control parameters, which is unsuitable for unstable systems with greater variations.

The authors in [23] proposed a new design for a higher-order repetitive controller that uses a phase lead compensator to improve the performance of the control loop in terms of variation handling capability. The research compares the performance of the proposed controller with that of a conventional repetitive controller under frequency variations and shows that the proposed controller outperforms the conventional controller. However, the proposed controller is designed specifically for repetitive current control of a two-level grid connected inverter. Therefore, the applicability of the proposed controller to other multilevel systems may be limited.

Various techniques are proposed to improve and support stability of to GFLI system under weak grid, for instance, the work in [24] uses PI control based VCC for control of GFLI in weak grid, the authors employed a second order filter for control and stable current regulation. Simulation results shows that, the PI –VCC with second order filter performance is good under strong grid without filter, however it requires a second order filter under weak grid for good performances and stable current regulation; but the use of second order increase operational cost and bandwidth of the filter will have effect on the system due to interaction with other system components.

The work by [25] proposed a simple and effective tuning method to stabilize PLL-based GFLI connected to extremely weak grid with SCR of one. Three control modes are considered in this tuning method includes current control, active power and voltage (PV) control, and active power and reactive power (PQ) control [25]. The current control deals with modification of the PLL natural frequency, modifying the structure of the conventional PI controller to IP controller [25], thus improving the stability and damping capability of the system under extremely weak grid. The other tuning modes deals with PV or PQ control been added as outer control loop, the loop ensure. The outer loop leads references of the inner current loop to achieve the desired PV or PQ control, so that voltage support from V control or Q control is based on the q-axis current, thus increasing the required active power. Simulation results shows the converter operates under extremely weak grid efficiently with the proposed scheme, however, addition of an outer loop increases cost and the IP controller may struggle with stability in the event of external disturbances or variations.

Several physical variables as seen from the point of common coupling (PCC) are found to contribute to the detrimental behavior of the VSC under weak connections [26]. To eliminate the impacts of these variables the work by [26] proposed open-loop feedforward (on the q-axis of outer loop) that significantly improves the active power capability. The open-loop involves feedforwarding the variables or their combinations through a modification of the existing structure, thereby partially eliminating their influence. Simulation results demonstrate the simplicity and intuitiveness of the proposed method. For better performance of direct voltage control (DVC) and alternating voltage control (AVC) [26], bandpass is required to mitigate ac and dc sides interactions which results in cost increase and complexity.

The work by [27] proposed a control topology of a conventional SRF-PLL with a feedforward frequency estimator loop with harmonic filtering capability, the work enhanced the synchronization capability of the of the PLL by improving the phase and frequency tracking of the GFLI under abnormal or weak grid condition. Simulation results shows that with the proposed method, the dynamics of the system is improved. However, additional hardware is required and tuning complexity may lead to overcompensation.

The work in [28] factored in the nonlinear dynamics of PLL and proposed a feedback linearization controller for a PLL-based GFLI to improve synchronization stability of the system under weak grid; by expanding the PLL domain of attraction to the whole plane that is limited to a small region around the equilibrium point in a conventional. While simulation results verified that the proposed controller expands the domain of attraction and enhances the system dynamic response. However, an additional method is required to estimate the system parameter due to variation and also, the feedback linearization cannot tackle the parameter variation and parameter uncertainty. which results in cost increase and complexity.

3. Theory

3.1 Grid following inverter system

Figure 1 illustrates the complete circuit topology of a 2-level-3-phase PLL based GFLI system, the system consist of DC side voltage (V_{DC}), three phase voltage source converter switching unit (GFLI), three phase LCL filter and damping resistance are modeled as (L_{f1abc}, R_{f1abc}) , (C_{fabc}) , (L_{f2abc}, R_{f2abc}) and (R_{df}) respectively. The line is modeled as the system impedance or transmission network as $\left(Z_{gabc}\right)$ and the grid or utility modeled as $\left(V_{gabc}\right)$. The measurement and transformation unit (abc–dq/dq-abc reference), current controller, pulse width modulation (PWM) or switching unit. The input to the measurement unit is the measured voltage, current at the PCC and the angular frequency $\left(V_{PCC}, I_{PCC} \text{ and } \omega t\right)$ respectively, while the output is the transformed parameters using park transformation as dq voltage and current $\left(V_{dq} \text{ and } I_{dq}\right)$; and vice-versa. The input to the current controller is the dq components $\left(V_{dq}, I_{dq} \text{ and } I_{dq}^{*}\right)$, while the output is the transformed three phase voltage used in controlling the switching sequence of PWM.

The GFLI system is modelled in terms of voltages and currents equations in dq-coordinate, and is expressed as equation (1):

$$\begin{bmatrix} V_{id} \\ V_{iq} \end{bmatrix} = \begin{bmatrix} R_f & -\omega L_f \\ \omega L_f & R_f \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} L_f & 0 \\ 0 & L_f \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} V_{pccd} \\ V_{pccq} \end{bmatrix}$$

(1)

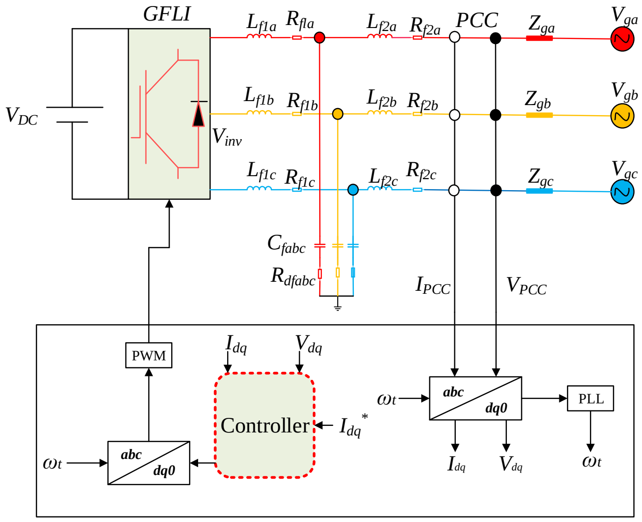

Figure 1. Grid Following Inverter System

3.2 The Synchronous reference frame phase locked loop (SRF-PLL)

The synchronous reference frame PLL (SRF-PLL) is the most widely used technology used for GFLIs applications [29, 30]. The Figure 2 shows the control block diagram of the three phase SRF-PLL. A three-phase voltage vector $\left[V_a \; V_b \; V_c\right]^T$ in the natural frame can be transformed into a vector $\left[V_d \; V_q\right]^T$ in the synchronously rotating reference frame by first using the Clarke transformation. Equation 2 shows the transformation for the SRF-PLL in Figure 2 [31].

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} E \,\mathrm{Cos}\left(\theta - \theta_g\right) \\ E \,\mathrm{Sin}\left(\theta - \theta_g\right) \end{bmatrix} \tag{2}$$

$$E = \sqrt{V_d^2 + V_q^2}$$

When the phase is locked, $E = V_d$ Hence, the frequency, the amplitude and the phase are all available from the SRF-PLL.

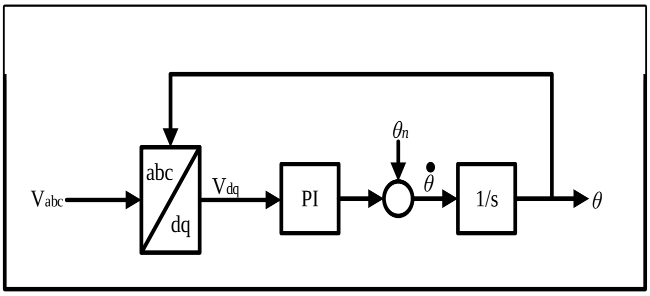

Figure 2. Three phase SRF-PLL

3.3 Vector Current Control

The vector current control (VCC) involves the use of control signals in the DC form, the control aspect is more flexible as DC variables are easily controlled. Figure 2 shows the vector controller as a form of control for the GFLI system. The controller or the regulator in the multi-input multi-output diagram depicted in Figure 3 can be linear or non-linear, e.g. PI, T-PIRC or enhanced PIRC (E-PIRC) in the case of the research study. The mathematical expression of the VCC for the GFLI is given as equations (3) and (4) for the d-axis and q-axis respectively., where $G_{controller}$ is the transfer function of the controller.

$$V_d^* = G_{controller}\left(I_d^* - I_d\right)\omega L I_q + V_d \qquad (3)$$

$$V_q^* = G_{controller}\left(I_q^* - I_d\right)\omega L I_d + V_d \qquad (4)$$

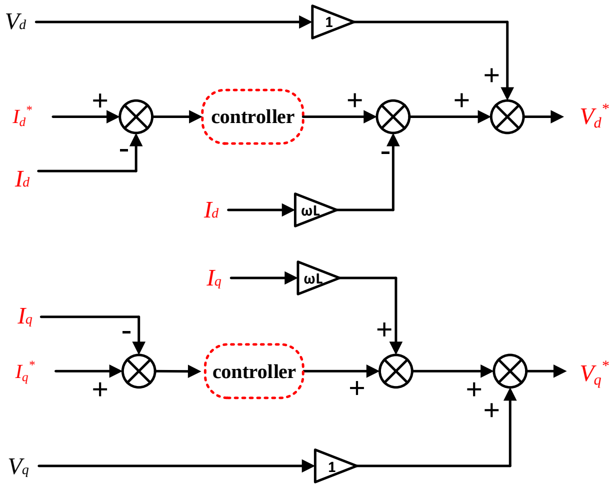

Figure 3. Vector current control for the GFLI system

4. Methodology

4.1 Traditional Proportional Integral Repetitive Controller (T-PIRC) Control

The conventional control is based on vector control as shown in Figure 3., the control uses the T-PIRC for the purposes of control and regulation of the system parameters required to inject the desired power according to the grid code specifications. The T-PIRC controller consists of proportional-Integral control (PI) and repetitive control (RC) to address current harmonic distortion and track periodic reference signals. The P-component generates a control signal that is proportional to the error signal generated as the difference between the reference or load signal $I_{dq}^*(z)$ and the converter output $I_{dq}(z)$ [32]. The I-component eliminates steady-state errors by continuously integrating the error signal generated over time [33]. Whereas, the RC-component allows the controller to track periodic reference signal $I_{dq}^*(z)$ [34]. In the context of the research work, the PIRC is assumed to be a combination of RC controller $\left(G_{RC}(z)\right)$ in parallel with proportional gain (k_p) with $P(z)$ as the plant model, and $\left(\Delta V_g\right)$ as the system disturbance due to weak and distorted grid condition. The Variable $C(z)$ is denoted as an internal filter or internal constant, N represents the number of samples for each cycle, determined as the ratio between sampling frequency $\left(f_s\right)$ ratio to the reference frequency $\left(f_r\right)$. The phase lead compensator $\left(z^m\right)$ addresses the system's phase lag resulting from the low pass filter and plant [35]. Additionally, the RC gain $\left(k_{rc}\right)$ and low-pass filter $\left(Q(z)\right)$ serve the purpose of attenuating. Figure 4 depicts the T-PIRC controller, together with the feedforward loop proposed to enhance the synchronization capability of the GFLI system. The transfer function for the conventional PIRC controller can be represented in the z-domain or as a discrete controller, it is given as equation (5):

$$G_{PIRC}(z) = K_{rc}\frac{C(z)z^{-N}}{1 - C(z)z^{-N}} \qquad (5)$$

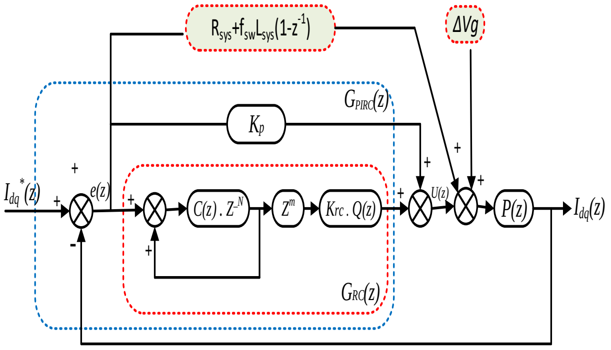

Figure 4. The T-PIRC plus the proposed feedforward loop (E-PIRC)

4.2 Proposed voltage feedforward to enhanced the PIRC (E-PIRC)

The tracking error $e(z)$ is the difference between the reference current $I_{dq}^*(z)$ and the converter output $I_{dq}(z)$. Assuming steady state condition is reached with the E-PIRC, the $e(z)$ is very close to zero, indicating improved tracking capability of the proposed controller in terms of harmonics rejection capability, thus proper information processing of the PLL is improved, due to control interaction improvement between VCC and the PLL dynamics.

4.3 Tuning of feedforward voltage gain

Under weak and distorted grid condition, voltage disturbance $\left(\Delta V_g\right)$ which occurs as the result of transition between strong grid voltage $\left(V_{sg}\right)$ to weak grid voltage $\left(V_{wg}\right)$ is given as the voltage difference at the PCC, and it results in current harmonics which degrades the tracking capability of the traditional RC. And because of the cascading effects of the current controller to the PLL dynamics, the disturbance will have cascading effects on the PLL. The processing capability of the PLL deteriorates which results to frequency instability in the system. Equations (6) and (7) represents the tracking error and system disturbance.

$$e(z) = \Delta I_{dq}(z) = I_{dq}^{*}(z) - I_{dq}(z) \tag{6}$$

$$\Delta V_g = V_{sg} - V_{wg} \tag{7}$$

To improve the tracking capability of the T-PIRC, a feedforward term is proposed within the traditional RC, the proposed feedforward term will help in mitigating the effect of voltage disturbance $\left(\Delta V_g\right)$, thus reducing steady state error and mitigating the cascading effects of the current controller on the PLL dynamics, thus improving the synchronization capability of the PLL while enhancing the system frequency stability.

The system impedance for strong and weak grid are given as equations (8) and (9) respectively, however during transition from high SCR to low SCR condition, the impedance change is represented as equation (10). The effect of the feedforward voltage is to mitigate the effect of the disturbance in the system, hence the change in line impedance will be assumed that the inductance is much under strong grid and the resistance is much under weak grid. Thus, neglecting resistance and inductance under strong grid and weak grid Equation (10) is to z domain using Laplace transform to z-transform, to achieve the required stability backward Euler method will be used to discretised the change in impedance. The relationship between s-domain to z-domain is given as equation (11), and for simplicity it will be assumed that both inductance and resistance will be approximated to system variables as $\left(L_{sys} \text{ and } R_{sys}\right)$ respectively.

$$Z_{sg} = R_{sg} + sL_{sg} \tag{8}$$

$$Z_{wg} = R_{wg} + sL_{wg} \tag{9}$$

$$\Delta Z = \Delta R + s\Delta L = R_w + sL_s \tag{10}$$

$$s = \frac{1 - z^{-1}}{T_s} = f_s\left(1 - z^{-1}\right) \tag{11}$$

$$\Delta Z = R_{sys} + f_{sw}L_{sys}\left(1 - z^{-1}\right) \tag{12}$$

The ratio of voltage feedforward term $\left(\Delta V_{ff}\right)$ to the tracking error is the gain is tuned as $\left(k_{ff}\right)$ the as depicted in figure, as given in equation (13).

$$k_{ff} = \frac{\Delta V_{ff}}{\Delta I_{dq}} = R_{sys} + f_{sw}L_{sys}\left(1 - z^{-1}\right) \tag{13}$$

4.4 Study parameters for the GFLI system

Table 1 represents the parameters used for the study, it includes both inverter and grid side parameters. While Table 2 indicates various SCR parameters with their respective corresponding line inductance and resistance. The parameters of the T-PIRC controller's components shown in Figure 3 are detailed in Table 3. The controller's six key elements for analysis include, the plant $P(z)$, proportional gain k_p, internal filter $C(z)$, low-pass filter $Q(z)$, compensator z^m, and the gain k_{rc} for RCs. Detailed discussions on the design of these components are provided in [36-37] respectively.

Table 1. GFLI and Grid parameters

Parameter	**Symbol**	**Value**
Inverter Side		
DC voltage parameters	V_{DC}	380V
Inverter filter	$L_{f1,2}$	3mH,2.5mH
	$R_{f1,2}$	0.48Ω,0.38Ω
	C_f, R_{df}	10μF,10Ω
Switching frequency	f_{sw}	10KHz
Resonant frequency	f_r	1KHz
Grid side parameters		
Grid voltage	V_g	415
Grid frequency	f_g	50Hz

Table 2. Line parameter at different SCR

SCR	**3**	**2.5**	**2**	**1.5**
R(Ω)	0.9975	1.1970	1.4962	1.9950
L(H)	0.0222	0.0267	0.0333	0.0445

Table 3. T-PIRC parameters

Parameter	**Specification**	**Value**
Phase lead compensation	M	8
Memory number	N	200
Proportional gain	k_p	19
RC gain	k_{rc}	25.21
Sampling time	T_s	0.02

5. Results and Discussion

Simulation studies were conducted within MATLAB/Simulink environment with various values of SCR condition, the variations of SCR condition allow simulation to be conducted in other to study both nominal and angular frequency behaviors as the grid impedances increases while also the SCR value decreases. The values of SCR used for the simulation studies are 3, 2.5, 2 and 1.5 the allows flexibility in investigating the effect of grid weakness increases on nominal frequency in terms of system stability and angular frequency in terms of PLL processing capability and overall control loop interaction and stability.

As depicted in figure 4, the graph is the simulation results of the GFLI system with T-PIRC, as can be seen the first column contains nominal frequency and angular frequency at a value of SCR=3 respectively, as be seen the nominal frequency oscillates within 50Hz, while the angular frequency is within the range of 6rads/s. While the subsequent columns represent the nominal and angular frequency response at SCR value of 2.5, 2 and 1.5, the response of the nominal frequency within the time range is almost ten-fold of the nominal value in both cases, thus indicating instability within the time range of 0.1s, hence that will trigger protection devices to operate. While for the angular frequency within the same SCR values, the values oscillate within 6rads/s, thus indicating PLL dynamics deteriorates as SCR increases.

While figure 5 indicates simulation results of the GFLI system with the E-PIRC, it indicates that in both SCR cases, the nominal frequency and the angular frequency are within their 50Hz and 6rads/s range respectively. Hence the in cooperation of the feedback loop within T-PIRC, helps to mitigate the effects of both frequency oscillations, thus enhancing control interaction between the VCC and PLL dynamics. Thus, the E-PIRC is able to improves system frequency stability, PLL processing capability, and can be seen that the E-PIRC control is more robust to the SCR variation.

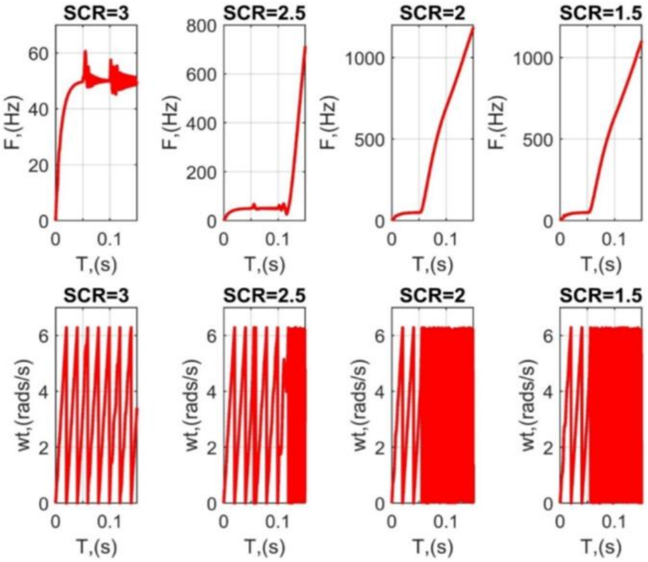

Figure 4. System nominal and angular frequency response with T-PIRC

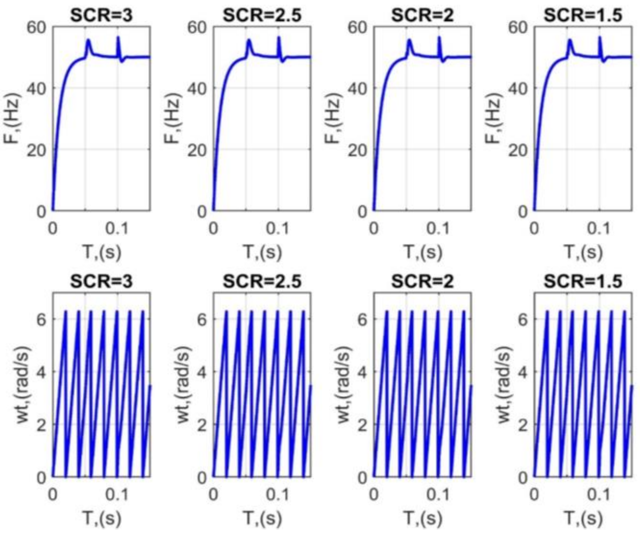

Figure 5. System nominal and angular frequency response with E-PIRC

6. Conclusion and Future Scope

GFLI is one of technologies used in inverter-based resources (IBR) for generation and integration of clean and renewable energy into an energized grid. However, traditional proportional integral repetitive controllers (T-PIRC) are one of the controllers used in the current control for control and regulation purpose; but under weak grid and low SCR their disturbance rejection capability deteriorates as shown via simulation. The deterioration leads to poor compensation of low order harmonics, thus leading to frequency instability and poor synchronization information capability of the PLL. The cascading effects leads to nominal frequency overshoot of almost tenfold the nominal value and oscillations of angular frequency all, due to impedance increase as a result of long distance and much converter penetration. To enhanced the performance of the T-PIRC, and enhanced version (E-PIRC) is proposed to improve system frequency stability and synchronization stability. The enhanced version proposed a feedforward loop that will assist the T-PIRC in providing enough compensation capacity under weak grid and high impedance. Simulations studies conducted, proved the effectiveness of the method, as under varying SCR conditions or long transmission distance the system stability in terms of frequency and synchronization are all improved, without addition of any new controller or control loop.

Future scope should include how protection gear will coordinate and work under weak grid without relay maloperations, also intelligent and AI based controllers are strong candidates for control purposes. In addition, hardware-in-the-loop (HIL) and power-hardware-in-the-loop simulation studies should be conducted to study the system behavior in real time.

Data Availability
Data used for the simulation studies can be accessed via the reference section as stated in section 4.4.

Conflict of Interest
Authors declare that they do not have any conflict of interest.

Funding Source
None.

Authors' Contributions
Inuwa Barau Inuwa- Conceptualization; Modelling; Methodology; Simulation; Validation; Visualization; Writing—original draft. Ahmed Shehu Timta- Simulation; Drawings; Writing, literature review-editing.

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