Research Article

Comparative Analysis of PI and PR Control Strategies for Enhancing Voltage Quality in D-Statcom-Based Distribution Networks

Fevzi Cakmak and Mehmet Emin Meral

***Abstract*—The rise in sensitive loads in distribution networks has highlighted the need to ensure uninterrupted electricity supply and maintain high power quality. In the current era, one of the most prevalent power quality issues in power systems is voltage sag, responsible for over 80% of the observed problems. Although the duration of the voltage sag is small (e.g. between 10 ms and 1 minute), it has a significant impact on the production process due to a small deviation from the nominal voltage. The disturbance can occur within a second, but the restoration process of the manufacturing system can take several hours. To improve the power quality or voltage quality of the grid, it is essential to regulate the reactive power. The objective of this study is to utilize a D-STATCOM for the correction of voltage by connecting it in parallel to the bus connection point between the grid and the loads. To investigate the contribution of a D-STATCOM with either a PI (proportional-integral) or PR (proportional resonance) controller in the system in response to a variety of fault scenarios causing voltage sags, a series of modeling and simulation studies have been conducted. These studies have involved commissioning various loads at low voltage (0.4 kV). The simulation of both models was performed using the PSCAD/EMTDC program. The performance of both controllers is evaluated through a comparison with the PSCAD/EMTDC simulation program. The results demonstrate that the D-STATCOM responds to short-term voltage sags caused by a fault or other system disturbances with a high degree of efficiency, rapidly restoring the bus voltage to a level close to the nominal value. This effectively mitigates the potential disruptions associated with voltage collapse. Furthermore, the analysis reveals that D-STATCOMs employing PI and PR controllers exhibit a combination of advantages and limitations in their performance.**

Index Terms— **D-Statcom, PI controller, PR controller.**

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Manuscript received Dec 11, 2024; accepted Dec 30, 2024.
DOI: 10.17694/bajece.1599674

I. Introduction

TODAY, the impact of sensitive loads on distribution networks is increasing. The rise in the number of these sensitive loads has prompted a corresponding increase in research into electrical power quality. Until a decade ago, the main concern of consumers was the reliability of supply, defined as the continuity of energy in the electrical system. Today, not only the continuity but also the quality of electrical power has become important to consumers [1].

Power quality problems must first be defined to solve them. In the present era, voltage dips represent one of the most prevalent issues about power quality. [2]. Voltage sags or dips cause more than 80% of the problems in power systems. A voltage trough is a short-term event (10ms to 1min interval) where a decrease in the effective voltage value occurs [2]. Although the period of deviation is relatively brief, a minor divergence from the rated voltage can precipitate a surge in costs. In numerous instances, the production process can be brought to a halt as a consequence of voltage sags. The disturbance may occur in a very short time, but the repair process may take hours. The effect of a voltage dip is the same as the effect of a power failure on power system equipment. In a system where the average number of outages is 1 per year, the number of voltage dips is approximately 80-90 per year. In this particular instance, the ramifications of voltage sags are more pronounced than those of power outages. [3]. The magnitude and duration of voltage dips are determined by two parameters [4].

Due to the generally inductive nature of loads connected to distribution networks and the increasing use of semiconductor power devices, these loads draw out-of-phase and non-linear currents. This creates electrical power quality problems in the network. In an ideal power system, frequency and voltage are expected to be constant, harmonics are expected to be absent, and the phase difference between current and voltage is expected to be approximately zero. These parameters, such as current, voltage, frequency, and harmonics, should be independent of the size and characteristics of the loads connected to the network [5].

In order to enhance the power quality of the network, it is essential to implement a reactive power control mechanism. In general, reactive power compensation is used for voltage regulation, load balancing, and load compensation [6].

In this case, there is a need for some devices (Custom Power) to regulate the voltage at the time of the fault and to provide quality voltage for sensitive loads. D-STATCOM (D-Statcom), which is one of these devices and is connected in parallel to the grid, is used as a Voltage Source Inverter (VSC) by regulating the voltage of the loads.

It is aimed to analyze and model the transient state studies of D-STATCOM connected to the power grid using the PSCAD/EMTDC program. In the D-STATCOM simulation study; predicting the performance of a system, identifying potential problems, and solutions to possible problems have been studied [7]. In this study, three-phase D-STATCOM is modeled under linear and nonlinear loads, and its performance is simulated using MATLAB software. The performance of D-STATCOM under linear and nonlinear variable loads in PFC (power factor correction) and ZVR (zero voltage regulation) modes is presented [8]. In reference [9], they have shown that other advanced controllers such as fuzzy controller, hysteresis current control, and the adaptive fuzzy controller can be used with D-STATCOM to improve the effectiveness of D-STATCOM in distribution networks. The mathematical equations of the equivalent circuit of D-STATCOM are presented [9]. A simulation model of D-STATCOM with a D-12-pulse inverter is designed using PSCAD/EMTDC simulation software for the mitigation of voltage sags caused by three-phase ground short circuit faults in distribution networks [10]. In this paper, the voltage source is comparatively analyzed using various control strategies such as converter-based, D-STATCOM, direct and indirect control including DQ transformation [11]. In D-STATCOM, the Sugeno Fuzzy Controller (SFC), Mamdani Fuzzy Controller (MFC), and PI controller have been studied to minimize voltage collapse and simulation results show that the Sugeno Fuzzy Controller (SFC) has the best performance among the three methods [12]. A novel D-STATCOM topology with a nonstiff source has been observed to reduce the size of the interface filter and the classification of the VSI (voltage source inverter) with improved current compensation capabilities [13]. Here, a self-tuning fuzzy set theory-based PI controller is designed for D-STATCOM. With the proposed fuzzy logic theory, the performance of D-STATCOM is analyzed and simulated for harmonic compensation for non-linear and linear loads [14]. An investigation of a five-level cascaded H-bridge (CHB) inverter as D-STATCOM in a power system (PS) for reactive power and harmonics compensation is presented. The advantages of the CHB inverter are shown to be low harmonic distortion, reduced number of switches, and reduced switching losses [15]. A D-STATCOM simulation with a switching control strategy based on sine pulse amplitude modulation (SPWM) for a two-level neutral-connected common voltage source converter (VSC) with an integrated inductor-capacitor-inductor (LCL) filter is simulated. To minimize the switching harmonic ripple in voltage and source currents, the interface between the VSC and the point of common coupling (PCC) is filtered using LCL filters. Better switching ripple attenuation was compared between the interface LCL filter and the L filter [16]. The implementation of D-STATCOM based on the voltage source converter injecting reactive power into the distribution line and using the PI controller has been realized in MATLAB/SIMULINK [17]. The performance analysis and operating principles of a new generation of power electronics-based devices (D-Statcom) aiming to improve the reliability and quality of power flow in the low-voltage distribution network are discussed [18]. The DC output from the PV source is amplified using a single step-up converter. The performance of five-level and seven-level D-STATCOM systems are compared in terms of THD and final receiver voltage. It has been shown that seven-level systems produce 20% higher output voltage with reduced THD [19]. In this study, state space modeling and voltage-controlled D-STATCOM are compared. An algorithmic approach is employed to generate a reference voltage for a distribution static compensator (D-STATCOM) operating in voltage control mode. The efficacy of this approach has been demonstrated in achieving a unit power factor (UPF) at the load terminal during nominal operation and in reducing the injection of currents and the associated losses in the voltage-induced inverter [20]. The static synchronous compensator (STATKOM) is modeled and the mathematical equations describing its behavior are presented. Simulation results of STATKOM controlled by PI controller are presented to prove the validity of the model [21]. Simulation of various special power devices such as DVR, D-Statcom, and Pwm Switched Auto Transformer to reduce voltage sags and swells has been carried out in the PSCAD/EMTDC programme for low voltages [22]. In this paper, a new online trained wavelet Takagi-Sugeno-Kang fuzzy neural network (WTSKFNN) controller is simulated with conventional proportional-integral (PI) controller to improve power quality such as distribution static compensator (D-Statcom), three-phase unbalanced currents compensation, total harmonic distortion (THD) reduction and power factor (PF) correction, and experimental results are given to verify its applicability and effectiveness [23]. This paper proposes the implementation of a Sliding Mode Controller Distribution Static Compensator (DSTATCOM) in order to enhance the quality of power supplied to distribution systems. The proposed solution is designed to address key issues such as harmonic removal, load balancing, and reactive power compensation, which are critical for maintaining the reliability and stability of power networks. This method is simulated in the MATLAB/SIMULINK platform to limit the variation of the DC link voltage within the limits [24]. In this study, it is stated that the performance of D-STATCOM in correcting the power quality decreases under instantaneous load variations. A new controller, an online trained polynomial petri-fuzzy neural network (PPFNN) controller is proposed to regulate the DC bus voltage. It is shown that the D-STATCOM controlled by the PPFNN controller regulates unbalanced currents, reduces the total harmonic distortion (THD) of current, and corrects the power factor in the microgrid with voltage support and droop control [25]. Distribution Static Compensator is proposed as a solution for harmonic, reactive power control, and neutral current compensation, which are power quality problems caused by sensitive, linear, nonlinear, and unbalanced loads. The proposed control method utilizes an Interval Type-2 Fuzzy Logic Controller (IT2FLC) with a Recurrent Least Squares (RLS) filter to generate switching pulses for the IGBT switches [26]. In this paper, a simulation model of a 750 kW hybrid (PV and wind) system in islanding mode is presented and it is shown that the use of DSTATCOM reduces the total harmonic distortion (THD) of the system [27]. This study presents the development of a hybrid control scheme based on the second-order super twisting algorithm (STA) and sliding mode control (SMC) for the inverter of DSTATCOM. The proposed control scheme for DSTATCOM was simulated in the SimPower system toolbox of MATLAB/Simulink. Both linear and nonlinear loads were considered, and the simulation results demonstrated that the super-twisted sliding mode control (STSMC) for DSTATCOM could rapidly regulate voltage sag/swell within 2,5 milliseconds for sensitive loads and could compensate for active and reactive power [28].

The aim of this study is to regulate the voltage by connecting D-STATCOM in parallel to the bus connection point between the network and the loads. In 0,4 kV low voltage distribution networks, modeling and simulation studies were carried out to investigate the contribution of D-STATCOM to the system using PI (Proportional Integral) and PR (Proportional Resonance) controllers for different fault scenarios causing voltage drops.

In the D-STATCOM controller, the difference between the reference voltage and the instantaneous measured load voltage enters the PR (Proportional Resonance) and PI (Proportional Integral) controllers as an error signal. PR (Proportional Resonance) and PI (Proportional Integral) convert the difference of this error value into an angular value. Sinusoidal PWM is used for the switching elements of the three-phase inverter connected in parallel to the mains. The two-stage VSD is connected to the grid side with a switch to provide instantaneous voltage support at the load. The voltage correction ratios of both PI and PR controllers and their response times to the fault occurring in the system are compared. In this study, the PSCAD/EMTDC software package is used for circuit modeling and simulation of PR and PI controllers, three-phase inverters, loads, and LC filters.

The article is structured as follows. In Section 2, the factors causing voltage sag are explained in detail. In Section 3, D-Statcom is explained in detail. Section 4 describes the proposed control algorithms in detail. In Section 5, the simulation results of the proposed PR algorithm and PI algorithms are compared and analyzed. Finally, conclusions are presented in section 6.

II. Factors Forming the Voltage Sag

A. Short Circuit Faults

For symmetrical and unsymmetrical short circuit faults, the three-phase short circuit has the greatest effect on the voltage sag [29]. To calculate the value of voltage sag in ring-connected distribution systems, the voltage divider model can be used as shown in equation 1.

In this context, ZH represents the source impedance at the point of common coupling (PCC), while ZA denotes the impedance between the PCC and the fault point, as shown in Figure 1. The voltage at the PCC can be expressed as [29];.

$$V_{sag} = \frac{Z_A}{Z_L + Z_A} E \quad (1)$$

B. The Activation of Large Loads

In Figure 1, starting a load, such as a high-power induction motor, is another important source of voltage drop. The starting current of an induction motor is approximately 5 to 6 times its rated current. The voltage sag across the busbar at the common connection point can be calculated from Equation 2 [30]. In the equation, ZH is the source impedance and ZM is the motor impedance at start-up.

$$V_{sag} = \frac{Z_M}{Z_L + Z_M} E \quad (2)$$

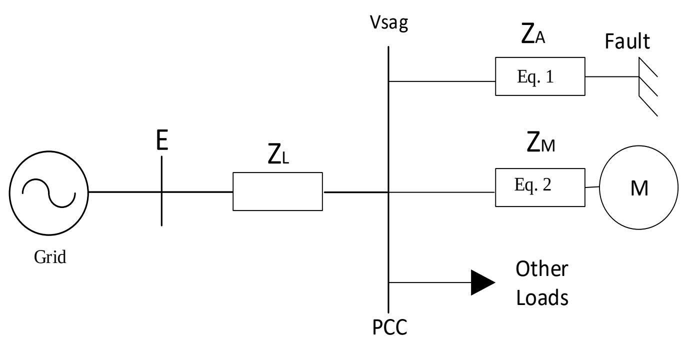

Fig. 1. Fault current generation in distribution networks and equivalent circuit for starting an induction motor

C. Energizing the Distribution Transformer

When the transformer is energized, the re-energized winding of the transformer, which saturates the core due to the residual flux on the core, draws an inrush current with high amplitude and harmonics from the mains. The inrush current is initially very high and after a while, it decreases to reach the small magnetizing current. To calculate the maximum value of the inrush current and the corresponding value of the voltage drop, the maximum value of the starting current should not exceed the current in Equation 3 [31]:

$$I_{inrush_{max}} = \frac{1}{X + X_P + Z_{CMİN}} E \quad (3)$$

Where X is the Thevenin equivalent reactance of the energized transformer and XCMIN is the minimum magnetization reactance of the transformer. Here XCMIN impedance is equal to 2(Xp+Xs).

Assuming that the leakage reactances of the primary and secondary windings are identical, the voltage sag value can be calculated as in equation 4 can be calculated as in [32]:

$$V_{sag} = \frac{X}{X + 2{,}5X_T} E \quad (4)$$

D-STATCOM is one of the fastest and most effective controllers of special power-consuming equipment. It is generally used to reduce voltage sags or surges in distribution networks and to enhance the power quality of the grid.

Special Power Devices are defined by IEEE (IEEE P1409, 2002) as follows Special Power Devices; The concept of power electronic controllers used to provide an appropriate level of power quality required for adequate performance of distribution networks with voltage up to 38 kV, associated industrial facilities and any production process in these facilities.

The basic structure of D-STATCOM consists of a two-stage voltage source inverter, an energy storage element, and a controller circuit [33], [34].

A D-STATCOM connected in parallel to the distribution network is used for three different purposes [35], [36]:

i. Regulation of the load voltage,
ii. Reactive power compensation,
iii. Elimination of current harmonics.

The D-STATCOM structure is based on a conventional sine wave PWM controlled two-stage voltage source converter (VSC). Figure 2 illustrates the single-phase equivalent circuit of the grid-connected D-STATCOM system. A number of factors must be taken into account when designing the D-STATCOM and associated control circuits:

i.Transformer ratio and reactance,
ii. Output filter elements,
iii. Two-stage inverter,
iv. DA capacitor.

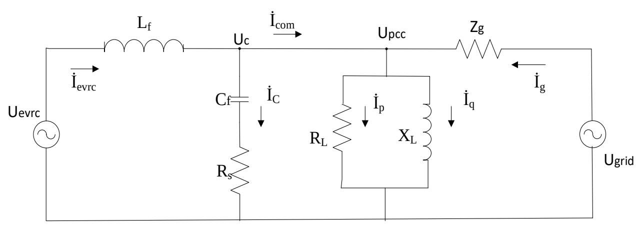

Fig. 2. Single-phase equivalent circuit of D-STATCOM connected to the grid with filter

The vector diagram of the circuit variables in Figure 3 shown in Figure 3 can be obtained.

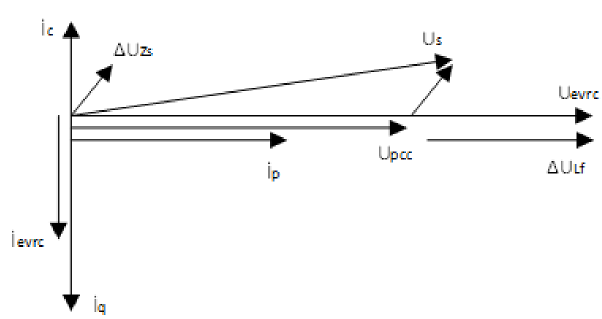

Fig. 3. Vector diagram of grid-connected D-STATCOM system

$$U_{evrc} = U_{pcc} + \dot{I}_{evrc} * X_{Lf} \tag{5}$$

$$i_c = U_c / X_{Cf} \tag{6}$$

$$i_c = U_c / X_{Cf} \tag{7}$$

$$\dot{I}_{evrc} = i_{com} - \dot{I}_c \tag{8}$$

If we assume that the variables shown in the vector diagram of the system are scalars; XLf = wLf, XCF = l / (wCf), the expression for the voltage sag of Lf can be derived from in equation 9.

$$\Delta U_{L0} = \dot{I}_{inv} * X_{L0} = \frac{(X_{C0} - X_L) * X_{L0}}{X_{C0} * X_L} * U_{pcc} \tag{9}$$

In a steady state, the common junction voltage Upcc remains constant. If the value of XLf is large, the value of ΔULf will increase. Therefore, by selecting a smaller value of Lf, the fundamental voltage sag of the inductor is reduced.

The reactive power compensation capability is transferred by the ratio between Ievrc and Icom.

In order to adjust the D-STATCOM output reactive current in a wider range, the Ievrc / Icom ratio should be above 95% according to the standards, but it is desirable to be close to 1. Having this ratio close to 1 means that much less power is consumed at Rs.

The expression Ievrc/Icom, which represents the reactive power compensation capability, can be derived from equation 10:

$$\frac{\dot{I}_{inv}}{\dot{I}_{com}} = 1 - \frac{X_L}{X_{C0}} \tag{10}$$

The higher the values of Lf and Cf, the lower the harmonic distortion rate; the maximum value of Lf is determined by the voltage drop; the maximum value of Cf is contingent upon the reactive power compensation capability. The designed filter parameters should therefore achieve a good balance between these three factors.

For a better filtering effect, a larger value of Lf, Cf should be selected, provided that the voltage sag of Lf does not exceed about 20% of the system voltage, and a value of Lf, Cf should be selected, provided that the ratio of Ievrc / Ic is not less than approximately 0.95.

The resonance frequency of the LC filter is defined by Equation 11 below:

$$f_c = 1/2\pi\sqrt{L_0 C_0} \tag{11}$$

Depending on the requirements for filter bandwidth and system stability, and to avoid excessive low-frequency response, fc is usually set in the mid-range.

$$10 f_n \leq f_c \leq f_s/10 \tag{12}$$

When designing filters, the following criteria are generally accepted;

I. The voltage sag across the filter should not exceed 20% of the mains phase voltage.

II. The power factor should be greater than 99.5%.

III. IEEE STD 519 current harmonics standard of 5.0% THD should be provided.

For large power systems, i.e. ISC/IL<20 (maximum short-circuit current (ISC), maximum load current (IL) [37].

IV. The resonant frequency should be greater than 10 times the mains frequency or half the switching frequency.

10fgrid < fres < 0.5fsw

The LC filter has a better effect than the single inductor filter circuit, so the LC filter is more commonly used. The design of the LC filter circuit is intricate and requires the consideration of numerous constraints [38]. The LC filter circuit can eliminate the effect of high-frequency harmonics at the inverter outputs; however, if the value of Lf is large, the D-STATCOM output currents will contain high-frequency harmonics. Under nominal operating conditions, a higher DC voltage is required. The smaller the Lf value, the lower the cost and the faster the dynamic response. If the Cf value is large, the current flowing through the resistor will increase and the resistor will consume extra power. It will also have poorer reactive power compensation capability.

D. *The Basic Principle of a DSTATCOM*

The configuration is founded upon the premise that two alternating current (AC) sources operating at the same frequency are connected through an inductance mechanism. In light of the aforementioned considerations, the single-phase equivalent circuit of the D-STATCOM is illustrated in Figure 4. In such a system, active power will transfer from the source in the forward phase to the source in the reverse phase, while reactive power will flow from the source with the higher voltage to the source with the lower amplitude. In other words, the active power flow between two AC sources is dependent upon the phase difference between the sources, while the reactive power flow is dependent upon the voltage difference between the sources [38].

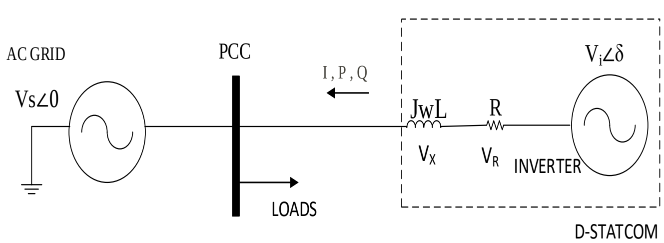

Fig. 4. Single-phase equivalent circuit of the D-STATCOM connected to the network

If the voltage Vs of the mains supply is taken as a reference, the active and reactive power balance will be as shown in Equation 13 and Equation 14.

$$P = \frac{V_s * V_i * \sin\delta}{X} \tag{13}$$

$$Q = V_s * \frac{V_s - V_i * \cos\delta}{X} \tag{14}$$

As shown in Figure 5, the D-STATCOM operating in inductive mode draws reactive power from the grid. As shown in Figure 6, D-STATCOM operating in capacitive mode supplies reactive power to the grid [39].

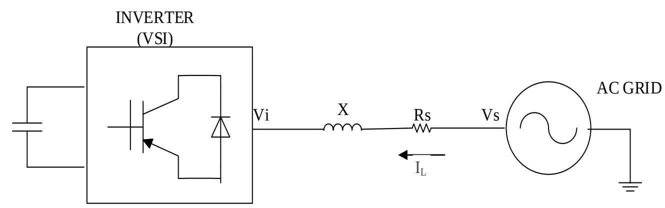

Fig. 5. Inductive mode operation

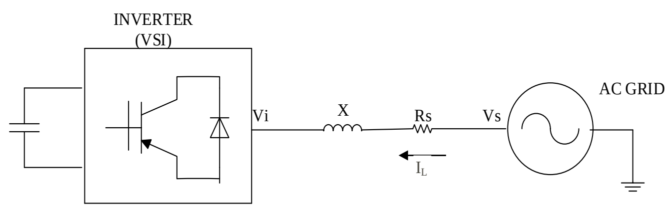

Fig. 6. Capacitive mode operation

III. The Control Methods

In this study, the method of control employed was that of monitoring the opening angle. The common point of reference was used to measure the current density, which was then compared with the reference current density to obtain a current density error. This error margin is applied to the PI or PR monitor as a control input. The output of the PI (Oransal İntegral) and PR (Oransal Rezonans) controllers is the phase angle δ of the main harmonic of the AC network voltage. The modulation index obtained from the fixed-value modulation index and the three-phase transformer primary winding parameters is used to generate PWM signals for the main circuit components. The aforementioned phase angle monitoring is illustrated in the PSCAD/EMTDC model in Figure 7. In this method, reactive power fluctuations can be monitored and controlled using suitable control and filter elements, with a response time of 2-5 periods [40].

The open-loop response time of the phase angle control is dependent upon the coupling inductance and the DC line capacitor within the system. The coupling inductance is employed to filter inverter harmonics, and higher values of this inductance will minimize the current harmonics of the D-STATCOM. However, a larger inductance than normal will result in a larger voltage regulation value on the DC line capacitor, in addition to the inverter input of the D-STATCOM operating from the inductive to the capacitive operation. It is therefore imperative that the selection of passive elements is made with the utmost care and precision to guarantee optimal performance in both steady-state and transient operational scenarios.

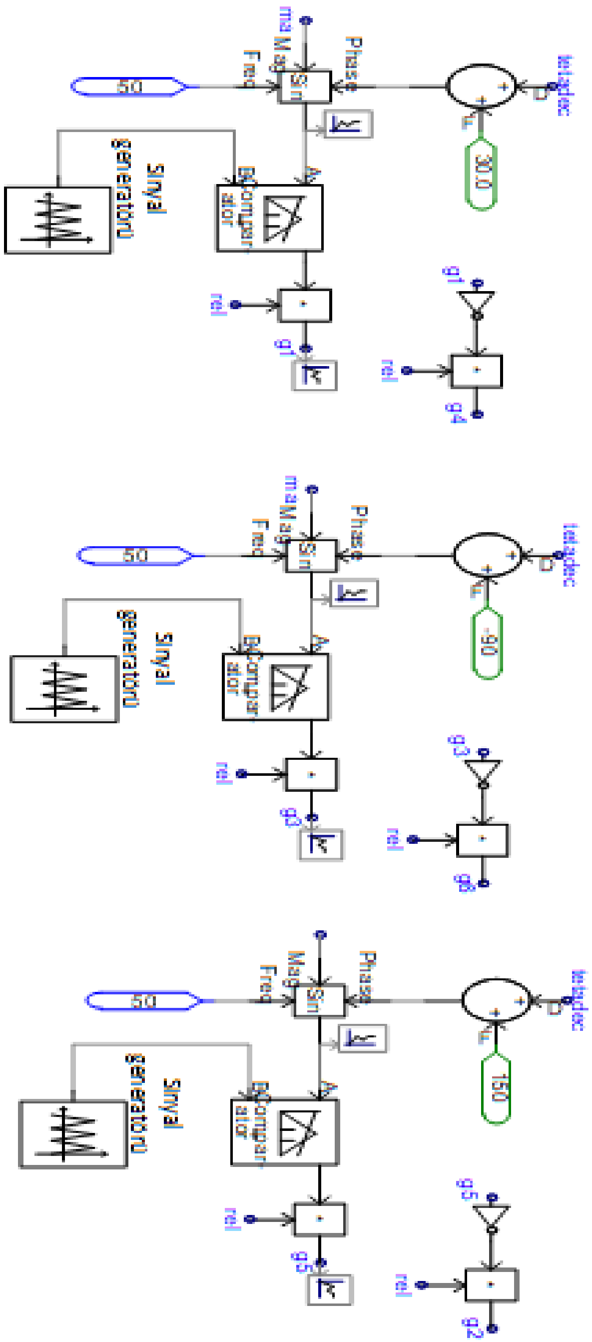

Fig. 7. PSCAD model for voltage quality improvement with phase angle control

A. Proportional Integral (PI) Controller

Figure 8 depicts the PI controller PSCAD model. The error signal, which is a function of the system's behavior, is evaluated in the controller and subsequently transferred to the output. The error signal, represented by e(t), is multiplied by the system gain, and the integral of the error signal is taken. The integrator in the system prevents an overshoot at the output. The output is increased or decreased by the value of the error signal, as determined by the proportional-integral (PI) controller.

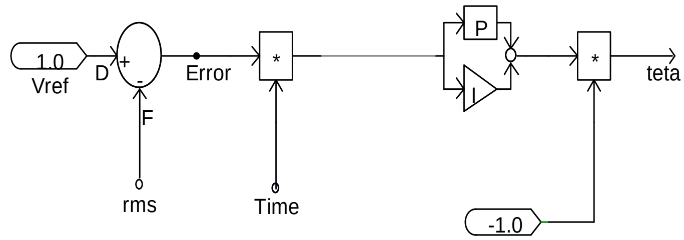

Fig. 8. PI controller PSCAD model

B. Proportional Resonance (PR) Controller

In the present era, the PR controller represents an efficacious methodology for the regulation of voltage in grid-connected inverters. The rationale for the deployment of the PR controller is to facilitate the streamlining and efficacy of harmonic compensation control in the context of nonlinear critical load conditions. PR constitutes a feedback current loop that oversees the mitigation of input voltage distortions and phase delays attributable to the LC filter. The optimal PR controller transfer function is delineated in Equation 15.

$$G_{PR} = K_P + \frac{K_i}{s^2 + \omega^2} \tag{15}$$

Where;
ω: The angular frequency of the network,
Kp: Proportional gain of the PR controller,
Ki: The integral gain of the PR controller.

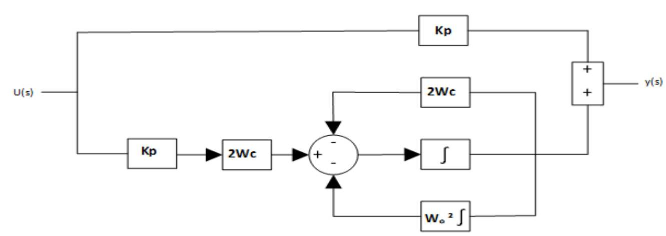

Fig. 9. Non-linear block diagram of PR Controller

As illustrated in Figure 9, the equilibrium response and the desired dynamic response of the system are dependent upon the constants Kp and Ki. The bandwidth of the controller, which serves to mitigate the impact of frequency fluctuations, can be diminished through the introduction of a cut-off angular frequency [40]. The PR controller is capable of eliminating harmonics present within the network by reducing the steady-state error to a level approaching zero. The nonlinear PR controller exhibits reduced gain and bandwidth at the resonant frequency, resulting in a negligible steady-state error between the reference and control signals. The frequency amplitude gain and bandwidth near the resonance point are contingent upon the integral time constant and demonstrate high dynamic performance. Conversely, the proportional gain Kp predominantly influences the controller's dynamic behavior. Figure 10 illustrates the PSCAD/EMTDC model of the PR controller.

 ISSN: 2147-284X

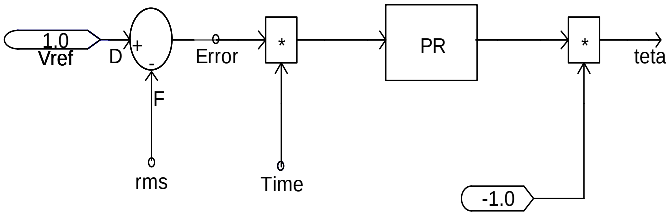

Fig. 10. PSCAD model of PR controller for D-STATCOM

IV. Simulation Results and Discussions

This study examines the potential of D-STATCOM to enhance voltage quality by addressing voltage drops (pits) in network voltage, including those caused by overcurrent loads and short circuit faults. Figure 11 depicts the block diagram of the general simulation studies of the D-STATCOM connected in parallel to the system. The system, for which a PSCAD model is provided in Figure 12, has been designed with the objective of enhancing voltage quality by eliminating the voltage sag problem, which is the most prevalent power quality issue, through the generation of a range of scenarios outlined below. The phase angle method was employed to control the D-STATCOM using two different controllers, namely PI and PR. The scenarios investigated were as follows:

a) Voltage sag scenario caused by an overcurrent load,

b) Voltage sag scenario due to both overcurrent load and three-phase short circuit fault,

c) Voltage sag scenario due to single-phase short circuit. A fault on both the overcurrent load and the source (grid) side

d) A voltage sag scenario due to both an overcurrent load and a three-phase short circuit fault on the mains side

e) A scenario in which a voltage sag occurs due to both the voltage sag in the mains (source) voltage and the voltage sag caused by the overcurrent load is presented.

In the system, the nominal load is continuously active. The 25% voltage sag error is created on the source (in the grid) side and the voltage sag occurs while the overcurrent-drawing second load is in the circuit. Then the second load is removed from the circuit and only a 25% voltage sag error is applied.

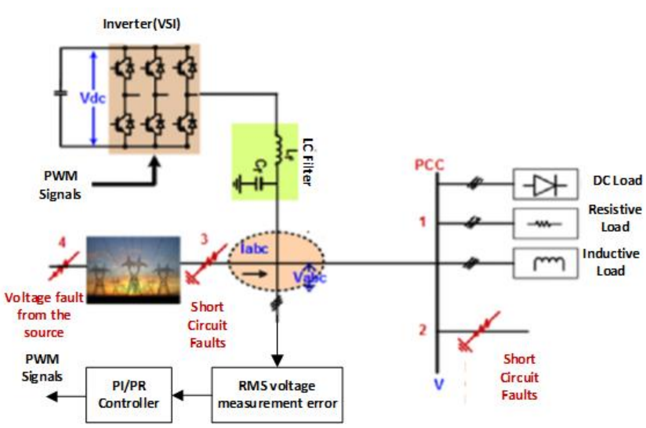

Fig. 11. Block diagram of general simulation studies of D-STATCOM connected in parallel to the system

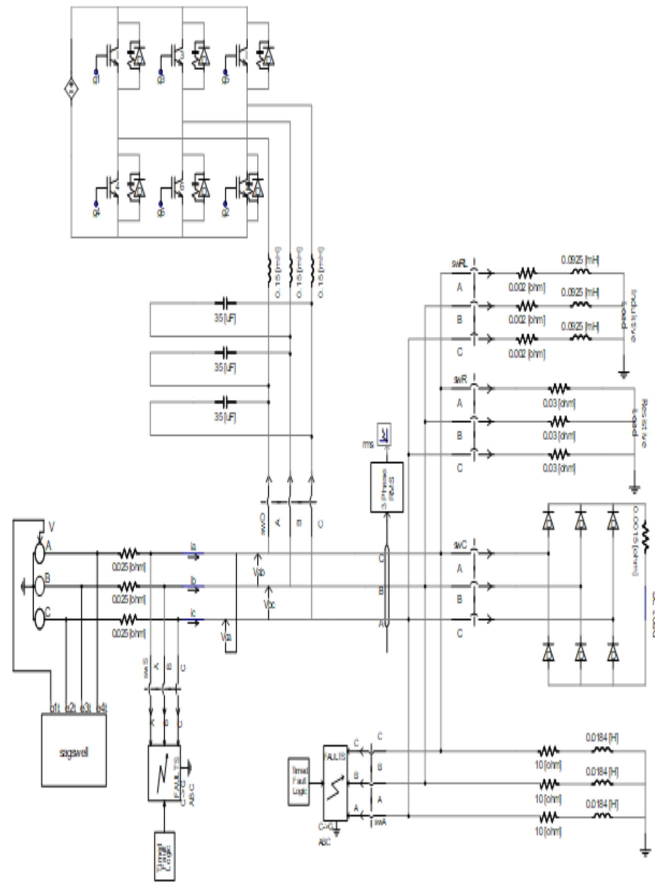

Fig. 12. PSCAD model of general simulation studies of D-STATCOM connected in parallel to the system

A. *Comparison of PI and PR Controllers According to Loads*

Figure 13 illustrates the load voltage stabilization times of PI and PR controllers for the voltage sag scenario resulting from the over-current-drawing load, DC load, resistive load, and inductive load, respectively. It can be demonstrated that the PI-controlled D-STATCOM exhibits a rapid response to voltage sag faults, with a time of 2.5 periods (50 ms), and the PR controller responds rapidly to faults in the system, with a response time of 1.25 periods (25 ms).

Table I illustrates the load voltage compensation ratios of the two controllers. The first column depicts the ratio of the voltage sag when D-STATCOM is not activated, while the second column represents the voltage increase ratio when D-STATCOM is activated. Upon examination of Table I, it becomes evident that the PI controller exhibits a greater capacity for voltage boosting than the PR controller during the voltage boosting process

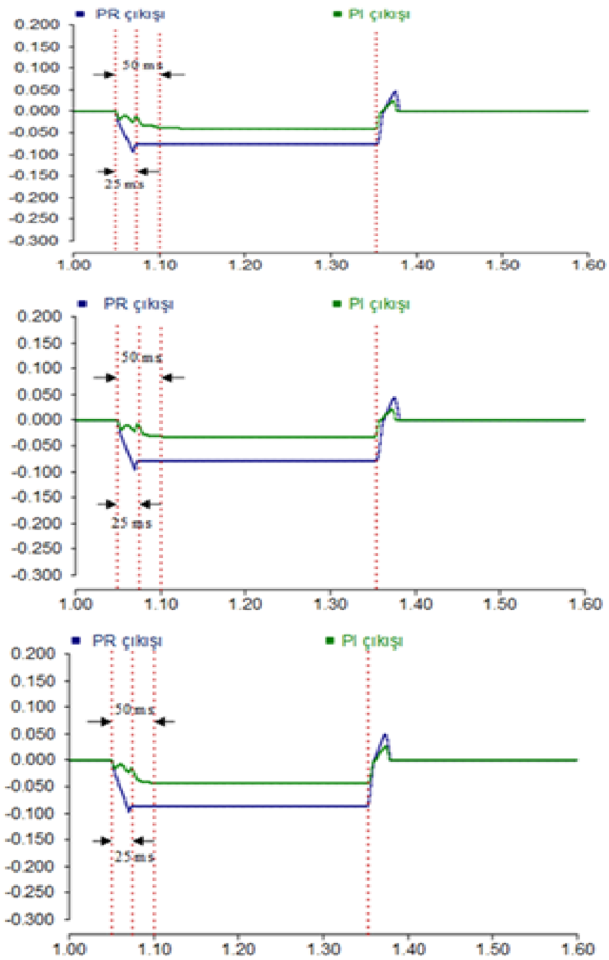

Fig. 13. . Output curves of PI and PR controllers according to loads (DC load, resistive load, and inductive load).

TABLE I
COMPARISON OF PI AND PR CONTROLLERS ACCORDING TO LOADS

Type of Controller	Voltage	DC Load (%)	Resistive Load (%)	Inductive Load (%)
PI Controller	Voltage Sag Ratio (when D-STATCOM is not activated)	74	74	73.5
	Voltage Swell Ratio (when D-STATCOM is activated)	95	96	94.5
PR Controller	Voltage Sag Ratio (when D-STATCOM is not activated)	74	74	73.5
	Voltage Swell Ratio (when D-STATCOM is activated)	92	92	91.5

B. Short Circuit Analysis by Load and Comparison of PI and PR Controllers According to Loads

The voltage correction level of the D-STATCOM was ascertained through the application of a three-phase short-circuit fault and an overcurrent load on the load side. Similarly, PI and PR controllers were compared for these loads and faults. Figure 14 shows that PR-controlled D-STATCOM (30 ms) responds faster than PI-controlled D-STATCOM (50 ms). In other words, PR-controlled D-STATCOM stabilizes the grid voltage 1 period (20 ms) earlier.

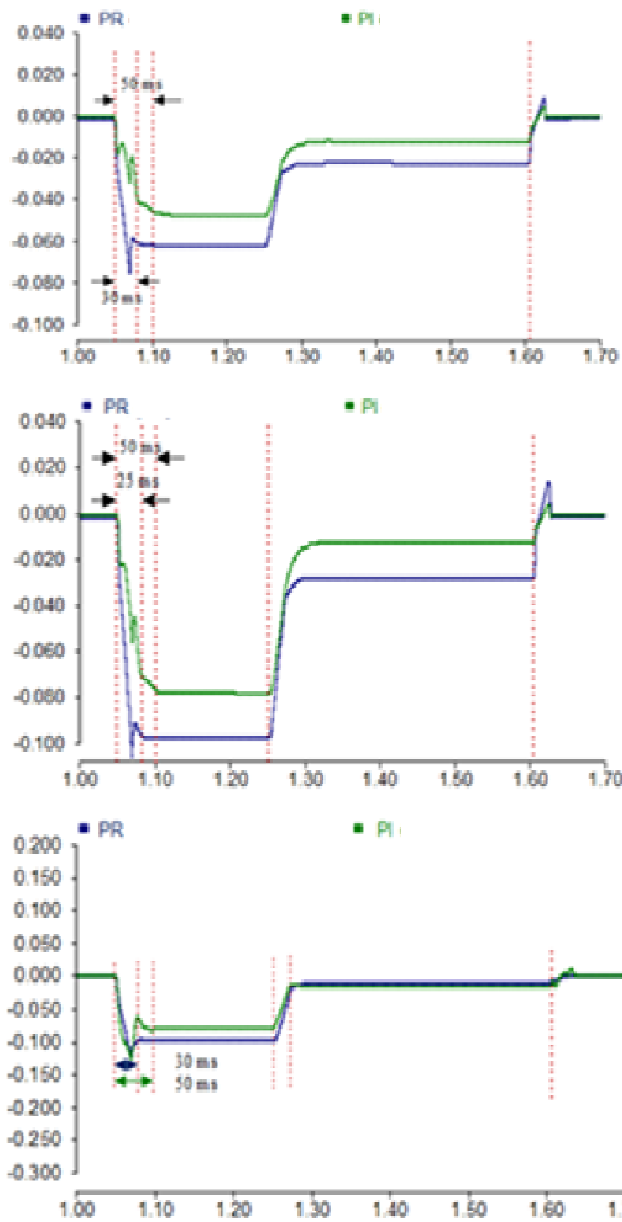

Fig. 14. Three-phase short-circuit fault on the load side and comparison of PI and PR controllers according to loads

The PI controller compensates more voltage than the PR controller, as shown in Table II.

TABLE II
SHORT-CIRCUIT APPLICATION BY LOAD AND COMPARISON OF PI AND PR CONTROLLERS BY LOAD

Type of Controller	Voltage	DC Load		Resistive Load		Inductive Load	
		Zone 1 (%)	Zone 2 (%)	Zone 1 (%)	Zone 2 (%)	Zone 1 (%)	Zone 2 (%)
PI Controller	Voltage Sag Ratio (when D-STATCOM is not activated)	25	22	28	25	31	25
PI Controller	Voltage Swell Ratio (when D-STATCOM is activated)	94	98.5	90	98	90	98
PR Controller	Voltage Sag Ratio (when D-STATCOM is not activated)	25	22	28	22	31	25
PR Controller	Voltage Swell Ratio (when D-STATCOM is activated)	92.5	96	90	96	90	98

Zone I: Both three-phase short circuit and overcurrent load
Zone II: Three-phase short-circuit fault

TABLE III
COMPARISON OF PI AND PR CONTROLLERS ACCORDING TO THE SOURCE SIDE VOLTAGE SAG APPLICATION AND LOADS

Type of Controller	Voltage	DC Load (%)	Resistive Load (%)	Inductive Load (%)
PI Controller	Voltage Sag Ratio (when D-STATCOM is not activated)	47	52.5	51.5
PI Controller	Voltage Swell Ratio (when D-STATCOM is activated)	92.5	96	95
PR Controller	Voltage Sag Ratio (when D-STATCOM is not activated)	46	52.5	51.5
PR Controller	Voltage Swell Ratio (when D-STATCOM is activated)	92	92.5	93

C. Comparing PI and PR Controllers According to Voltage Sag on the Source Side and Loads

There is a voltage sag of 25% on the grid (source) side. Since there is a voltage sag on the source side, the current drawn by the rated load also decreases at the same rate. However, when the secondary loads (resistive load, inductive load, and rectified DC load) are activated, they draw excessive current from the mains and cause a voltage sag. Initially, a voltage sag is created by both the overcurrent loads and the voltage sag error (25%) created on the mains side.

As can be seen in Figure 15, when comparing the PI and PR controllers with DC load, resistive load, and inductive load, i.e. with the same error and the same loads, the PR controller works faster than the PI controller. In other words, it stabilizes the mains voltage more quickly. On the other hand, as can be seen from Table III, the PI controller increases the voltage more than the PR controller.

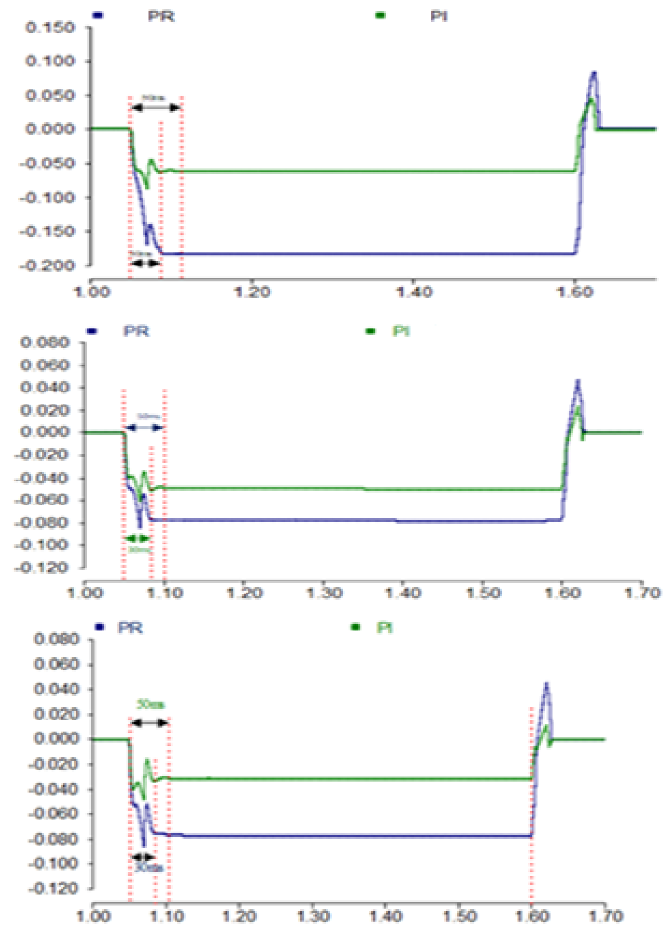

Fig. 15. Comparison of PI and PR controllers according to source side voltage sag and loads

D. Source-Side Short-Circuit Analysis and Comparison of PI and PR Controllers According to Loads

As can be seen in Figure 16 b (with resistive load), when comparing the PI and PR controllers for the same system and loads, it can be seen that the PR controller works faster than the PI controller. In other words, it makes the grid voltage more stable faster. In Figure 16 a and Figure 16 c, PI and PR stabilize the droop voltage at the same time for the DC load and inductive load.

In this study, a D-STATCOM model connected to a low-voltage distribution system is established and its performance in compensating for voltage troughs is investigated through the use of simulation studies. The phase angle control method offers the benefits of a straightforward algorithm and a simple implementation process. However, the method has certain limitations, including the inability to independently control active and reactive power and the potential for significant current fluctuations due to its inability to regulate the current.

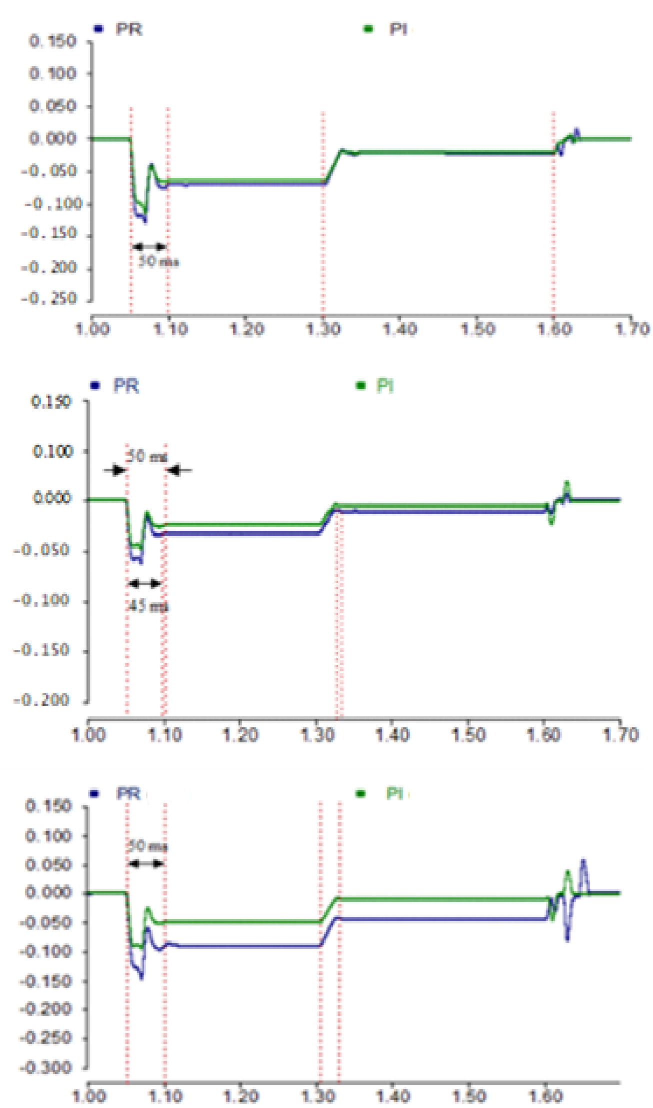

Fig. 16. Comparison of PI and PR controllers with respect to three-phase short-circuit faults occurring as the source and loads

Table IV shows that the PR controller provides more voltage increase than the PI controller for three short-circuit faults occurring on the source side during voltage increase.

In the modeling, a D-STATCOM two-level inverter and LC filter design compatible with 0.4 kV distribution networks have been implemented. This study compares the performance of a PI-controlled D-STATCOM and a PR-controlled D-STATCOM under various load conditions and different fault scenarios.

TABLE IV
COMPARISON OF PI AND PR CONTROLLERS WITH RESPECT TO THREE-PHASE SHORT-CIRCUIT FAULTS OCCURRING AS THE SOURCE AND LOADS

Type of Controller	Voltage	DC Load		Resistive Load		Inductive Load	
		Zone 1 (%)	Zone 2 (%)	Zone 1 (%)	Zone 2 (%)	Zone 1 (%)	Zone 2 (%)
PI Controller	Voltage Sag Ratio (when D-STATCOM is not activated)	27	20	26	20	26	20
	Voltage Swell Ratio (when D-STATCOM is activated)	92.5	97	94	98	94	98.5
PR Controller	Voltage Sag Ratio (when D-STATCOM is not activated)	27	20	26	20	26	20
	Voltage Swell Ratio (when D-STATCOM is activated)	93	98	93	98	90.8	95

Zone I: A combination of a three-phase short circuit fault and an overcurrent load
Zone II: A three-phase short circuit fault

The system is subjected to a voltage sag as a result of the connection of DC, ohmic, and inductive loads, which draw excessive current and cause a reduction in voltage. The effect of the D-STATCOM on the load voltage was investigated, with and without the device activated. The voltage correction values of the two controllers at varying load levels are presented in Table 1. Table 1 demonstrates that the D-STATCOM is an effective and rapid solution for voltage correction. A comparison of the PI and PR controllers reveals that the latter responds more rapidly than the former. Conversely, during voltage boost operation, the PI controller exhibits a greater capacity for boosting voltage than the PR controller.

In the event of an overcurrent load in the circuit, a three-phase short circuit fault on the load side is also analyzed. The D-STATCOM is capable of increasing the voltage of the load to the desired rate in this instance. Table 2 presents a comparison of the PI and PR controllers in the context of short circuit applications and loads. It can be observed that the PR controller exhibits a faster response than the PI controller in the event of a short circuit; however, the PI controller demonstrates.

In the event of an overcurrent load within the circuit, a 25% voltage sag fault was also applied on the source side. The load voltage was subjected to analysis under two conditions: with and without the presence of D-STATCOM within the circuit. Upon activation of the D-STATCOM, an increase in the load voltage to an acceptable range (90% to 110%) as defined by the IEEE standard was observed. Table 3 presents the results of the voltage sag application on the source side and a comparison of PI and PR according to different loads. Accordingly, the PR controller demonstrates superior voltage stabilization compared to the PI controller, although the difference is minimal. Conversely, the PI controller exhibits a greater capacity to increase voltage.

A three-phase short circuit fault is applied to the source side in the event of an overcurrent load in the circuit. When the PI and PR-controlled D-STATCOM are in operation, it increases the voltage of the load to the desired level. Table 4 illustrates the voltage ratios in the event of D-STATCOM activation. In the short circuit fault application on the source side, a comparison of the PI and PR controllers for a resistive load reveals that the PR controller operates more rapidly than the PI controller. However, at a DC load and an inductive load, the PI and PR controllers achieve the desired outcome in a similar time frame. It can be observed that the PI and PR-controlled D-STATCOM demonstrate superior voltage regulation at resistive and inductive loads.

V. Conclusion

Today, the most common power quality problem is voltage sags. Voltage troughs constitute 80% of power quality problems. D-STATCOM is used to mitigate voltage sags/swells in distribution networks and to improve power quality in the network. Studies show that D-STATCOM can successfully alleviate voltage troughs and bring the busbar voltage to the desired limit values.

As a result, it has been observed that D-STATCOM effectively compensates for the voltage sags caused by loads that are suddenly switched on. In addition, it is also observed that it prevents the system from dropping by keeping the load voltage constant against short circuit faults on the load side and on the grid side, and corrects the power factor by exchanging reactive power. In general, it is seen that both controllers efficiently enable D-STATCOM to fulfill its desired function, PR controller provides faster response, on the other hand, PI controller provides up to 5% more voltage compensation than PR under the same conditions. In linear systems, PI and PR controllers with fixed parameters have been found to respond well to the phase angle method.

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