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ive Legged Power Converter (FLPC) for Augmenting Power Quality in Hybrid Solar-Wind System

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***Abstract_** Solar and wind energy become auspicious electricity generation resources. Integrating these resources provide greater advantages, yet the power system quality is affected because of the varying nature of wind and solar energies that cause voltage problems, high harmonic distortion and less transient stability issues. To combat these problems, we proposed a five-legged harmonic remover based on time-invariant power converter, which initially converts alternative current (AC) obtained from the plant into direct current (DC) without any power loss using three-phase bridge rectifier. Then the high frequency component in DC is blocked by a nonlinear capacitor. Subsequently, the false current is removed using Fault current remover and sent to Diode based DC to AC converter for transforming DC into AC. Finally, the converted AC is passed over a bridge based c type filter to remove harmonics. By this way, the proposed system has achieved better power quality.*

***Keywords:** Three phase bridge rectifier, Nonlinear capacitor, Fault current remover, DC to AC converter, C type filter.*

I. INTRODUCTION

Over the past few years, renewable energy resources attained major observation. Among those wind and solar energy are universally available and eco-friendly resources. Hence, combining these two sources profitably gives prominent consistency as the strength of one system overwhelms the weakness of other [1].

Furthermore, combining this hybrid system with grid enhances the consistency of renewable electricity generation to fulfill the loads [2]. However, a prominent optimum sizing method is essential to utilize renewable energy resources effectively, which ensures a complete usage of system components at low investment and makes the hybrid system to run properly. Some optimization techniques established for ideal hybrid renewable energy systems are probabilistic approach, linear programming, and graphic construction methods.

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Moreover, the energy storage system was utilized for providing a continuous supply of electricity and for facing the shortage of power generation, which includes battery banks, fuel cells, etc.

but it increases the investment. Hence, another method should be utilized for attaining ideal hybrid renewable energy framework [3]. In remote areas, it is impossible to get long-term climatic conditions like wind speed and penetration of solar irradiance, which is necessary for sizing procedures. Therefore, artificial intelligence approaches are utilized for replacing conventional sizing procedures.

Grid-connected systems influence, power quality, like harmonics, frequency, and voltage changes [4]. Moreover, the fluctuating natural surroundings of solar and wind energies affect the consistency of the system. This may be reduced by exact predicting and scheduling [5]. Hence, many methods and algorithms were developed for forecasting the climatic changes which enable the system operator to alter other available generating systems, while any deficit rises, which in turn minimizes the fluctuations [6]. Energy stocking components were utilized to balance the shortage and to stock the energy while a large amount of energy is generated [7].

However, voltage fluctuation remains the main concern which is caused by irregular solar irradiance and varying wind speed. The fluctuations of voltage mainly depend upon the type of load and its dimension along with dimension and strength of the integrated grid. Certain dynamic power filters like static synchronous compensators, integrated power quality conditioners, and dynamic voltage regulators were developed as a solution for this voltage wavering problem [8]. Likewise, power compensators were utilized for diminishing the dynamic power issues due to wavering voltage issue, which are the recent interface among user consumption and grid.

Abrupt dynamic power variations caused by the load produce frequency variation in AC grids, which symbolizes the unsteady state among generation and load. Hence, a pulse width modulation (PWM) inverter is designed for controlling frequency and power to diminish quality issues [9]. Certain filters and PWM inverter reduce harmonic distortion, which usually arises in all non-linear appliances and power electronic devices [10]-[12]. Albeit they fail to deluge the multi-order harmonics along with frequency and voltage wavering which demands a proficient harmonic remover. Besides, an appropriate optimization technique is obligatory to guarantee partaking ideal quantity and dimension of solar panel and wind turbine [13]. Furthermore, an optimum sizing technique is essential to effectively predict solar radiation and wind speed [14] for keeping enough source of electricity to fulfill the demand.

Thus, the hybrid system includes both wind and solar have been in very much need of incorporation of the best optimization along with the robust forecaster to efficiently and economically utilizes the electricity generated from the hybrid system. The residual outline of our research paper is specified underneath. **Section 2** explains some researches associated with this proposed paper, **Section 3** describes the entire working procedure of our proposed five-legged power converter,

Section 4 illustrates the results and discussions obtained by implementing the proposed method and **Section 5** provides the conclusion of this framework.

II. LITERATURE WORK

Certain prevailing researches related to our proposed framework discussed briefly underneath:

Merabet et al. [15] presented rationality depended on a power administrative scheme for program swapping of lights' banks. This system utilized the power generated through wind turbine, which gets regulated through a pitch angle regulator approach. An enhanced PI regulator was developed to mitigate the wavering issues. The results corroborate the efficacy of the power management system in the wind turbine. However, high harmonics and frequency components were ignored in this method.

Karakasis et al. [16] developed an initialization procedure for a doubly-fed induction generator (DFIG) wind system. It gives the smooth initialization procedure along with the least power depletion from the energy stocking unit. To give less iron rotor losses, the DFIG functions at the synchronous speediness in the stand-by circumstance. Numerous implementation outcomes were provided to show the proficiency of their stratagem.

Sitharthan et al. [17] proposed a Feed Forward Back Propagation Neural Network (FFBP-NN) depend upon the pitch angle regulator output and the power wavering in the grid integrated wind turbine. In this, the ideal output power is predicted and smoothened. Moreover, the Levenberg–Marquardt (LM) procedure was utilized for training FFBP-NN. Results proved that their proposed network performed well. Yazan M. Alsmadi et al. [18] presented a complete review on the LVRT of grid-connected DFIG-based wind turbines. This paper specifies active performance as well as the transient features during the voltage drops along with implementations. Also, it developed an innovative rotor side regulating strategy to DFIG-based wind turbines for improving LVRT competence while major voltage drop occurs, which in turn enhance the performance of DFIG. Its proficient enactment was verified by comparing it with prevailing regulating strategies.

Hector Pulgar-Painemal [19] developed logical lexes for applying rotor and stator power restrictions utilizing DFIG capability curve (DFIG-CC), which was compared with two generally utilized stratagems. Logical lexes was checked in 15-bus test system comprises of five wind turbine generators (WTG) and attained greater accuracy when compared to prevailing strategies. From these researches discussed above, it is obvious that our proposed methodology has to overcome the voltage fluctuation problem, harmonic distortion, transient stability issues by designing a robust converter which can manage constant voltage, low harmonic distortion and obtaining constant optimal transient stability.

III. FIVE LEGGED POWER CONVERTER (FLPC)

Demand for current is growing vastly; hence, substitution is necessary for generating electricity without affecting the environment and should be an easily available resource. Hybrid systems become a promising source as it integrates wind and solar resources for generating electricity. An assembly of connected solar cells known as the solar panel utilized for generating electricity. Similarly, a wind turbine contains an electric generator, which generates electricity by converting wind energy into electrical energy. The solar panels and wind turbines greatly depend upon the fluctuating climatic conditions. If solar and wind gets combined as one system, the solar system generates high electricity during summer as the solar radiance is high, whereas the wind turbine generates high electricity during winter since the velocity is high. However, the generated current has a variable frequency, which is transferred to the desired grid voltage using these hybrid solar-wind systems. The power system quality is affected because of the varying nature of solar and wind energies that causes voltage problems, high harmonic distortion, and less transient stability issues. Fluctuating wind velocity affects the voltage of the DC link and also produces fluctuating torque. Moreover, since most of the converter uses nonlinear elements to store energy intermediary and voltage and current filtering; the cost, weight, and size of the converter get increased, and this leads to degradation in power quality and less transient stability. As a solution to the problems, this work has proposed a five-legged harmonic remover based on time-invariant power converter, which avoids high harmonic distortion and upgrade the quality of power in power plants. Since this system has taken into account the following criteria: power loss, fault current and high-frequency component, this system can combat high harmonic distortion and maintains power quality and transient stability. Figure 1 describes the overall procedure of the Five Legged Power Converter (FLPC).

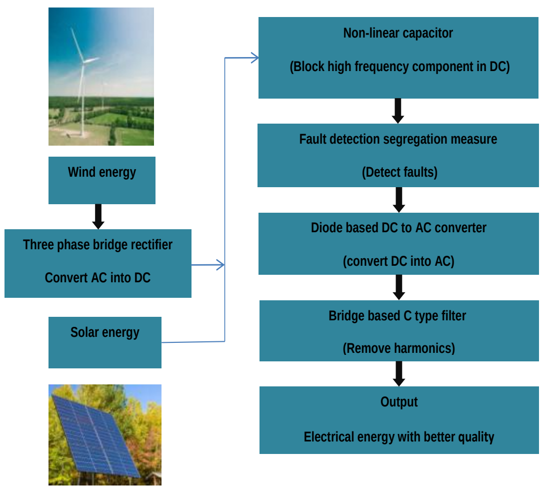

Figure 1: Block diagram of the Five Legged Power Converter (FLPC)

Initially, alternative current from the plant would be converted into direct current without any power loss using three-phase bridge rectifier then to block the high- frequency component in the direct current nonlinear capacitor is adapted. Subsequently, the false current is removed by incorporating Fault current remover. After being removed the fault, the direct current permitted through Diode based DC to AC converter for altering DC into AC. Finally, the alternative current experiences harmonics, hence abridge based c type filter is adapted to remove harmonics. By this way, the proposed system has achieved better power quality.

A. Three Phase Bridge Rectifier

A three-phase bridge rectifier, utilized for converting AC that sometimes flows in the reverse direction into DC that flows in a single direction. It comprises of six thyristors and utilizes controlled solid state gadgets such as IGBT's, MOSFET's, SCR's, etc. for varying the power at diverse voltages. The output power at the load is changed suitably by activating these gadgets. The diagrammatic representation of the three-phase bridge rectifier circuit, displayed in figure 2.

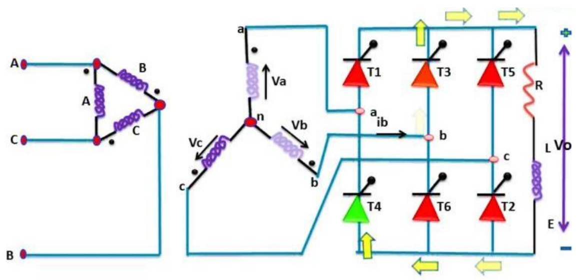

Figure 2: Three phase bridge rectifier

If the current has to flow, anyone gadget from the upper set (T1, T3, T5) and anyone from the lower set (T2, T4, T6) should conduct electricity. Generally, every thyristor conducts at 120^o of the input cycle, and its conducting is in the series T1 → T2 → T3 → T4 → T5 → T6 → T1 along with an interval of 60^o among every conducting. Hence the thyristors conduct at 180^o interval along the same phase leg and are not capable of conducting instantaneously, which in turn provides six probable modes for conducting, i.e., T1T2, T2T3, T3T4, T4T5, T5T6, T6T1. Every conducting way has 60° interval and seems like the above-said series. To minimize the voltage of the output,

$$D_v = A_v = \frac{3 \cdot \sqrt{3} \cdot P_v}{\pi} \cdot \cos(\theta) \tag{1}$$

(Or)

$$D_v = A_v = \frac{3 \cdot P_{L-Lvolt}}{\pi} \cdot \cos(\theta) \tag{2}$$

Here:

D_v represents the DC output voltage, , A_v represents the average output voltage.

$P_{L-Lvolt}$, the peak voltage of the line to the line input,

P_v , the peak voltage of phase input,

θ Symbolizes the angle of conducting of the thyristors.

These conditions (1) and (2) reduce the output voltage only when the current is not obtained from the AC source or else if the AC source has no inductance as in theory. But practically, the output voltage decreases when the load is increased, which is caused by the source inductance. Consequently, every conversion among a set of gadgets causes overlap while three gadgets conduct instantaneously, which is usually 20-30^o at the fully loaded condition.

While considering the source inductance, the output voltage will be:

$$D_v = A_v = \frac{3 \cdot P_v}{\pi} \cdot \cos(\theta + \lambda) \tag{3}$$

(Or)

$$D_v = A_v = \frac{3 \cdot P_{L-Lvolt}}{\pi} \cdot \cos(\theta) - 6\gamma I_c P_d \tag{4}$$

Here:

I_c , the commutating inductance per phase,

P_d , the direct current,

γ denotes the frequency.

Thus the entire AC obtained from the renewable resources is converted into DC without any power loss; though it contains high frequency. Hence it is to be removed to obtain better power quality.

B. Nonlinear Capacitor

The non-linear capacitor used for reducing high-frequency constituents exist within the converted direct current (DC). Surface-based packages are tiny, and shortage linking leads utilized for capacitors. These modules prevent unwanted high-frequency impacts because of the leads as well as its simple automated assemblage. The value of capacitance based on the voltage applied. Figure 3 presents the diagram of the nonlinear capacitor with a rectifier. It also smoothes the DC obtained from the rectifier. The primary function of the nonlinear capacitor is to destroy the high frequency in the source and to smooth the output waveform of the rectifier.

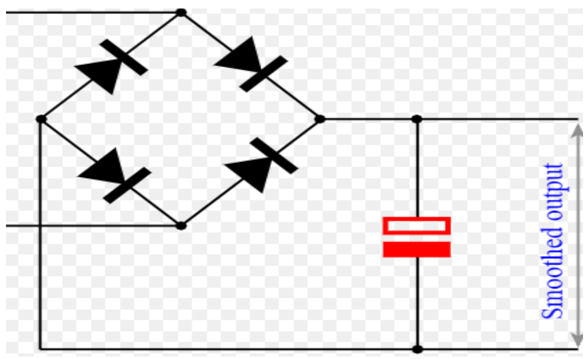

Figure 3: Rectifier with capacitor

The capacitance is represented by,

$$C = \frac{E}{C_v} \tag{5}$$

Where C is the capacitance, E is the charge through the capacitor, and C_v is the voltage on the capacitor.

The high-frequency signals removed from the entire direct current, and thus the DC signals are free from higher frequencies. These signals are passed to the current fault remover to nullify the fault current.

C. Fault detection segregation measure

Fault detection segregation measure (FDSM) detects the faults without a whole breakdown. FDSM is added to show the output of the uncertain input observer when faults are effectively observed and isolated

. A simple circuit diagram of FCR shown in figure 4

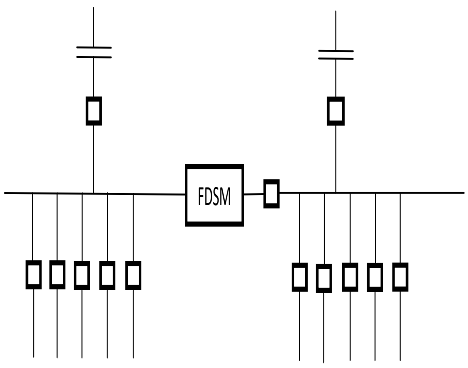

Figure 4: Simple circuit with FCR

Generally, a circuit breaker is provided in large power systems to cut off power supply while a fault arises, however, for enhancing reliability, a smaller region where the fault present should be detached. The circuit breaker can't withstand while incorporating other sources such as wind turbines and solar panels. Hence, we utilize current fault remover for eradicating the fault currents present in the system.

A current fault remover is a nonlinear component that has high impedance during fault current and low impedance during the normal current. Thus the current fault remover detaches the section which contains fault current and again does the regular function. The current removal section includes a switch and limiting resistance and has two dissimilar restraining characteristics for removing temporary as well as permanent faulty states. While a fault occurs, it is removed by restricting the impedance of the main circuit. The load gets supplied to the main circuit after the fault gets repaired. If the fault is permanent, the faulty features limited for a certain specified time after that the connection is detached.

The restricting resistance required to obtain an assured voltage regulation is

$$\frac{\Delta V}{V_p} = \frac{R_e}{R_e + R_l} \times 100 \qquad (6)$$

Here V_p represents the voltage in the power system,

R_e , equivalent resistance,

R_l , limiting resistance.

The fault current gets removed using limiting resistance, and the entire operation does not get stopped because of the fault; instead, a small unit is shutting down.

D. DC to AC Converter

DC to AC Converter is an electronic equipment that alters DC into a suitable AC which gets mixed into the electricity grid network. The foremost function of these converters is to keep up a higher the output voltage than the grid and also it should be suitable for the grid. It generally contains a sensor that continuously monitors the waveforms and the voltage of the grid. A figure 5. shows primary DC to AC converter. The DC output of current fault remover is transformed, to provide electricity in the form of AC, using the DC-AC converter. It reduces the intricacies produced during operation and also the expense.

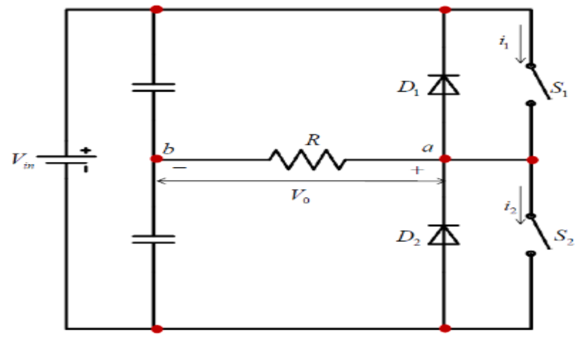

Figure 5: Basic DC to AC converter

The switch S_1 is on at duration $0 \le t \le T_1$ and the switch S_2 is on at duration $T_1 \le t \le T_2$. The voltages through a load while either S_1 or S_2 are on

$$V_l = \frac{V_i}{2} \qquad (7)$$

The output voltage has aRMS value of

$$RMS_v = \left(\frac{1}{T_1} \int_0^{T_1} \frac{V_i^2}{4} dT \right) = \frac{V_i}{2} \qquad (8)$$

The output voltage waveforms of ideal converters are sinusoidal. Though, the waveforms hold definite harmonics.

III.5. C Type Filter

C-type filters eradicate harmonic constituents effectively. For that here L_2C_2 section has been finely modified to a necessary harmonic frequency which in turn diminishes the dynamic power losses.

Hence the harmonics are not able to pass the R resistor, and thus they prevent major losses. The entire circuit of the C-type filter shown in figure 6.

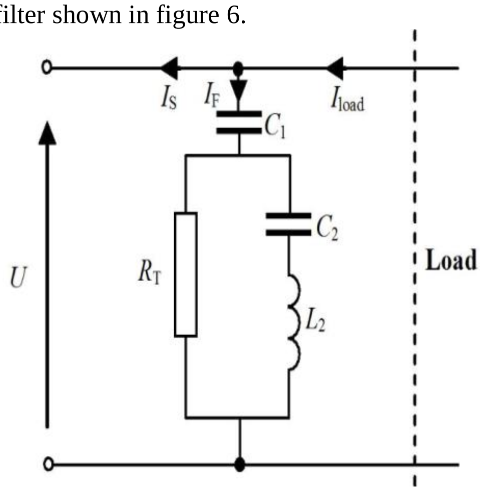

Figure 6: C-type filter

Likewise, n^{th} harmonic wave constituent transferred via a filtering capacitor C ; the capacitance should be lesser when compared to the impedance, i.e.,

$$|\Im_L| = \sqrt{(R)^2 + (n\omega L)^2} >> \frac{1}{n\omega C} \quad (9)$$

It should fulfill the following condition:

$$|\Im_L| = \frac{10}{n\omega C} \text{ (Or) } \frac{|\Im_L|}{10} = \frac{1}{n\omega C}$$

As well as the impact of the load is insignificant. Similarly, the capacitance selected is the entire load impedance divided by 10. Thus the harmonics in the alternating current are nullified, and the power transferred to the grid.

IV. METHODOLOGY, RESULTS AND DISCUSSION

After Executing the circuit used in our proposed five-legged power converter, their results are presented in this section to corroborate the proficiency of this proposed framework.

In this method, at first, we convert AC obtained from the renewable energy resources into DC utilizing three phase bridge rectifier. The DC coming out of the three-phase bridge rectifier has high frequency; hence, this high frequency has to be avoided using a nonlinear capacitor. Then the high frequency removed DC is allowed to pass through the Fault current remover to eradicate the fault current present in it. Consequently, the DC is converted into AC to utilize by the utility grid. For that, here in our framework, we provide Diode based DC to AC converter that alters DC into AC. Finally, the AC attained from Diode based DC to AC converter still has harmonics; and hence remove the harmonics. Hence, we utilize a bridge based c type filter for eradicating the harmonics in AC.

A. System Specification And Experimental Setup

MATLAB/Simulink executes our projected system in the working platform of MATLAB with the following system specification. The simulation results for this methodology discussed below.

Platform	: MATLAB 2015a
OS	: Windows 8
Processor	: Intel core i5
RAM	: 8 GB RAM

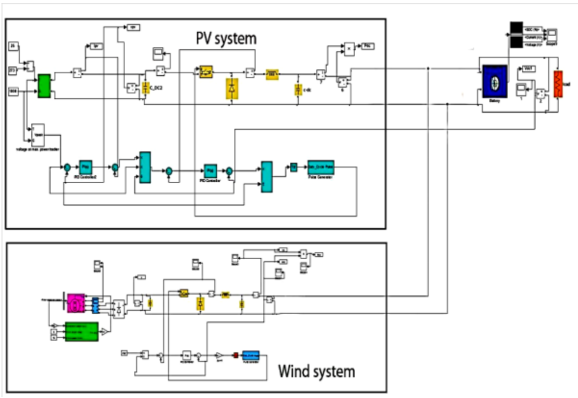

Figure 7: System architecture of proposed FLPC

Fault Current Remover:

Fault current remover performs removing false current arising in three phases; the table shows the current removed esteems. The outcome obtained by using current fault remover, tabulated in the table, and also the simulated results presented in figure 8.

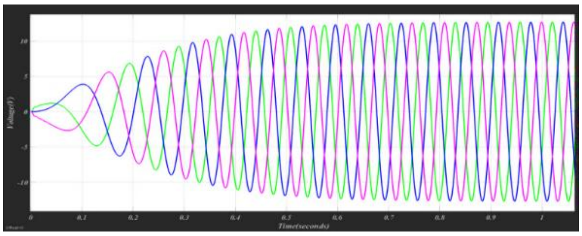

Figure 8: Output of voltage after feeding with Fault Current Remover

Table 1: Output of Fault Current Remover

Time	Phase 1	Phase 2	Phase 3
0.0566	0.954111445718174	1.48946544885249	-2.44357689457066
0.0874	-1.19370838581800	3.46817736505849	-2.27446897924049
0.1333	-4.72518369899824	0.818501743908422	3.90668195508983
0.1876	6.56605804867848	-4.52573875138444	-2.04031929729403
0.2459	-8.19471015348042	2.99892374809389	5.19578640538653
0.2930	8.86260518506204	-1.84691010605079	-7.01569507901124
0.3612	8.87239671614082	-9.36021643825522	0.487819722114399
0.4637	-6.54161624513099	11.6230806304386	-5.08146438530759

C-Type Rectifier:

The C-type rectifier eliminates the harmonics that present in the alternating current. The below tables 2 and 3 provides the results before and after passing through the C-type filter. The simulation results obtained by implementing the method specified in figure 9 and 10.

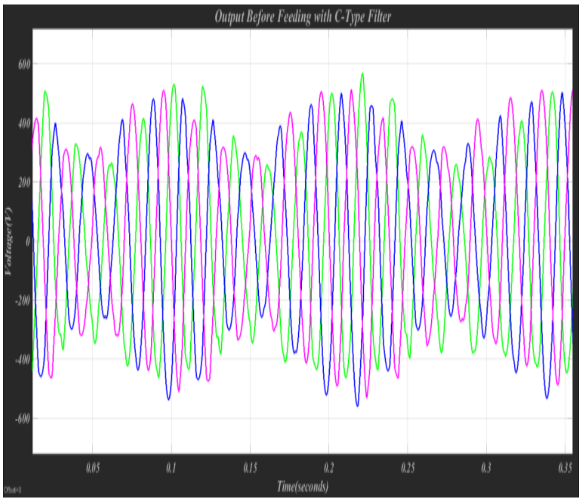

Figure 9: Output before Feeding into the C-Type Filter

Table 2: Output of Voltage before C-Type Filtering

Time	Phase 1	Phase 2	Phase 3
0.0604	110.255978485910	-145.236999418236	34.9810209323294
0.1203	253.825943995602	-259.045625048347	5.21968105276397
0.1804	104.199956932179	-216.293200561568	112.093243629386
0.2403	251.331384251916	-228.272724560411	-23.0586596914694
0.3004	84.5655105860001	-154.315325787988	69.7498152019846
0.3603	208.633653306810	-325.025923356449	116.392270049652
0.4204	247.625063147645	-177.578034946010	-70.0470282015832
0.4803	103.166620255859	-134.621522969276	31.4549027133762

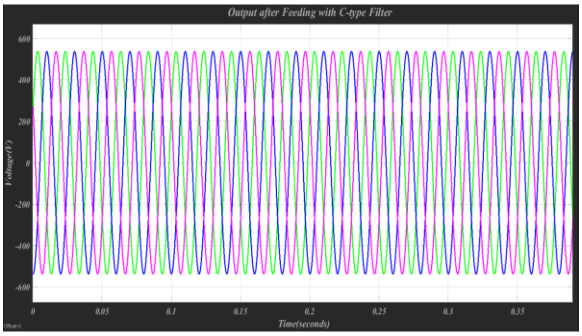

Figure 10: Output after Feeding with C-Type Filter

Table 3: Output of Voltage after C-type Filtering

Time	Phase 1	Phase 2	Phase 3
0.0604	43.1810572145814	-287.676129915165	244.495072700584
0.1203	28.8394325856906	-281.957032094028	253.117599508337
0.1804	43.1810572145798	-287.676129915165	244.495072700586
0.2403	28.8394325856902	-281.957032094028	253.117599508338
0.3004	43.1810572145838	-287.676129915167	244.495072700583
0.3603	28.8394325856897	-281.957032094028	253.117599508338
0.4204	43.1810572145789	-287.676129915163	244.495072700583
0.4803	28.8394325856937	-281.957032094027	253.117599508333

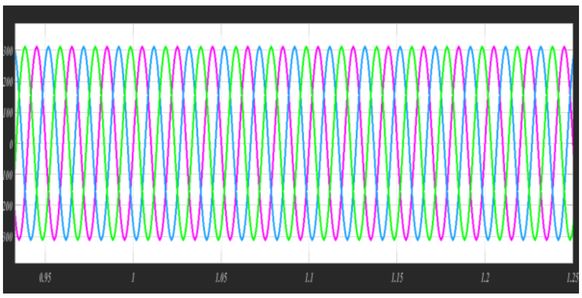

Figure 11: Voltage output for existing

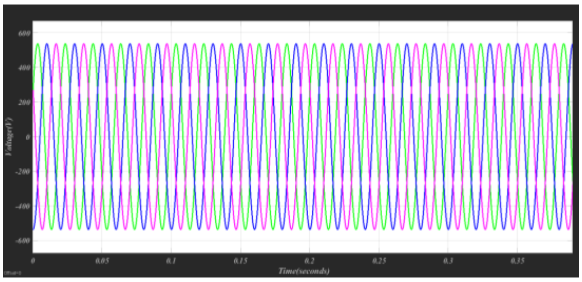

Figure 12: Voltage Stability for Proposed System

Voltage stability of our proposed system corroborated in figure 12. Thus, our proposed method Five Legged Power Converter attains high voltage stability than the existing techniques.

B. Experimental Metrics

The simulation of the proposed Five Legged Power Converter (FLPC) evaluated with the metrics such as

i. Electrical Efficiency η_e ,
ii. Frequency Variations,
iii. Voltage Imbalance/Unbalance V_i ,
iv. Voltage Dip (Sag) and Swells,
v. Deviation of Supply voltage magnitude,
vi. Total Harmonic Distortion (THD).

1) Electrical Efficiency

Electrical efficiency by the proportion of the amount of electrical energy given as input to the amount of electrical energy obtained as output. Generally, Electrical efficiency expressed in terms of percentage.

$$\eta_e = \frac{I_{out}}{I_{in}} \times 100 \qquad (16)$$

$$= \frac{I_{in} - losses}{I_{in}} \times 100$$

$$\eta_e = 1 - \frac{losses}{I_{in}} \times 100 \qquad (17)$$

2) Frequency Variations

Frequency is a change in the way, alternating current (AC) flows. The Indian utility power grid provides a frequency standard value of 48.5 Hz to 51.5 Hz.

3) Voltage Imbalance/Unbalance

Voltage imbalance demarcates as the proportion of negative series constituents to positive serve constituent usually expressed in terms of percentage.

$$V_i = \frac{Negativeseriesvoltage}{Positiveseriesvoltage} \times 100 \qquad (18)$$

4) Voltage Droop and Surges

Voltage droop represents the drop of Root Mean Square (RMS) voltage amongst 0.1 to 0.9 Pu in at a period of 0.5 cycles to 1min. A surge represents the rise of RMS voltage within 1.1 and 1.8 Pu at a period of 0.5 cycles to 1 min.

5) Deviation of Supply voltage Magnitude

Long-term deviations of supply voltages include RMS deviances of power frequencies for more than 1 min.

6) Total Harmonic Distortion (THD)

The primary metric for ensuring quality is Total Harmonic Distortion (THD). THD demarcates as the proportion of the RMS esteem of the entire harmonics to the RMS esteem of its fundamental signal. Here, the signal is the quantified current or voltage.

THD is represented by

$$\text{Total Harmonic Distortion (THD)} = \frac{I_H}{I_F} \quad (19)$$

Where $I_H = \sqrt{I_2^2 + I_3^2 + \ldots.. + I_n^2}$, and

I_H RMS esteem of H_{th} harmonic;

I_F signify RMS esteem of fundamental current.

Evaluation metrics that are estimated to prove the efficacy of FLPC described in terms as above tabulated in table 4. The evaluation metrics taken in our method are:

i. Electrical Efficiency η_e ,
ii. Frequency Variations,
iii. Voltage Imbalance/Unbalance V_i ,
iv. Voltage Dip (Sag) and Swells,
v. Deviation of Supply voltage Magnitude,
vi. Total Harmonic Distortion (THD).

Table 4: Esteems of evaluation metrics

Sl. No	Parameter	Inverter with general HPS	MG with refabricated HPS	FLPC
1	Electrical Efficiency	91%	90%	92.34%
2	Frequency	±0.40%	±0.21%	±0.19%
3	Deviation of the load voltage	Noisy	Smooth	Very Smooth
4	Deviation of grid voltage	Noisy	Smooth	Very Smooth
5	Voltage Droop	44%	29%	25%
6	Voltage Surges	41%	32%	31%
7	Voltage Imbalance	12.50%	2.13%	2.02%
8	Total Harmonic Distortion	4.89%	4.59%	4.06%

The values of evaluation metrics obtained for proposed framework Five Legged Power Converter (FLPC depicts as table 4), justifies that our proposed method attains efficient power quality in terms of low power loss, low frequency, minor harmonic distortion and reduced false current.

V. CONCLUSION

This paper proposed a Five Legged Power Converter (FLPC) to provide better power quality for hybrid wind and solar systems as the existing systems have certain drawbacks such as power loss, the uncertainty of wind energy nature and solar irradiance which causes voltage problems, high harmonic distortion and less transient stability issues. Hence, our proposed framework FLPC has taken into account the following criteria: power loss, fault current and the high-frequency component, this system can combat with the high harmonic distortion and maintained the power quality and the transient stability of the wind turbine. Henceforth, we utilized three-phase bridge rectifier to convert alternating current-direct current without any power loss, then a nonlinear capacitor is adapted for blocking high-frequency component. Moreover, to nullify the false current, Fault current remover is incorporated. Subsequently, the direct current is transformed into AC utilizing Diode based DC to AC converter. Consequently, the harmonics existing within the alternating current are removed using a bridge based c type filter. Thus, our proposed system FLPC has achieved better power quality. The simulation results substantiate that our proposed system has a low power loss, low frequency, reduced false current and, minor harmonic distortion. Therefore, the proficiency of the proposed framework Five Legged Power Converter (FLPC) presented in this paper.

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