

CASCADED MULTILEVEL INVERTER BASED TRANSFORMER-LESS UNIFIED POWER FLOW CONTROLLER

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ABSTRACT: In this paper, a cascaded multilevel inverter based transformer-less unified power flow compensating scheme is proposed. The topology consists of three level cascaded multilevel inverter for both shunt and series compensations. To overcome the disadvantages of conventional transformer based UPFC and thus as an improvement a transformer less based UPFC is designed. The shunt compensated inverter is connected directly across the transmission line, while the series compensator is connected to the transmission line via linear transformer. The DC link voltage maintenance is the main concept and challenge in cascaded multilevel inverter based facts devices since the source of the inverter is capacitors. The dc-link voltages of the inverters are regulated at different levels to obtain three-level operation. The system behaviour is analysed for various operating conditions. The simulation study is carried out in MATLAB/SIMULINK to predict the performance of the scheme under balanced, unbalanced and fault conditions.

KEYWORDS: Cascaded multilevel inverter(CMI),Flexible ac transmission system(FACTS) transformer-less UPFC.

I. INTRODUCTION

The application of flexible ac transmission systems (FACTS) controllers, such as static compensator (STATCOM) and static synchronous series compensator (SSSC), is increasing in power systems. Because they have the ability to stabilize the transmission systems, reactive power compensation, active power oscillation damping, flicker attenuation, voltage regulation and to improve power quality (PQ) in distribution systems. Generally, in high-power applications, var compensation is achieved using multilevel inverters. These inverters consist of a large number of dc sources which are usually realized by Capacitors. Hence, the converters draw a small amount of active power to maintain dc voltage of capacitors and to compensate the losses in the converter. However, due to mismatch in conduction and switching losses of the switching devices, the capacitors voltages are unbalanced. Balancing these voltages is a major research challenge in multilevel inverters. Various control schemes using different topologies are reported in [2]–[5]. Among the three conventional multilevel inverter topologies, cascade H-bridge is the most popular for static var compensation because of its advantages like absence of clamped diodes and reduced number of capacitors [3], [4]. However, the other types requires a Large number of dc capacitors. The control of individual dc-link voltage of the capacitors is difficult.

When the multi-level converter is applied to a STATCOM, each of cascaded H-bridge converters should be equipped with an isolated and split dc capacitor without any power source or circuit. This allows us to eliminate a bulky, heavy and costly line-frequency transformer from the cascade STATCOM. Static var compensation by cascading conventional multilevel/ two level inverters is an attractive solution for high-power applications.

The idea of the unified power flow controller (UPFC) was first proposed by Gyugi in 1992. Since then, as the most sophisticated flexible ac transmission systems (FACTS) device, the UPFC has been researched widely and many papers dealing with UPFC's modeling, analysis, control, and application have been published in recent ten years. The UPFC combines the functions of several FACTS devices and is capable of realizing voltage regulation, series compensation, and phase angle regulation at the same time, thus realizing the separate control of the active power and reactive power transmitted simultaneously.

The conventional UPFC has been put into several practical applications, which requires an interface transformer to isolate each inverter from the transmission line. In addition to isolation, traditional high-voltage high-power inverters that often are 48-pulse for desired high-quality waveforms have to use bulky and complicated transformers to reach their required VA ratings (from several megawatt volt-ampere to hundreds of megawatt volt-ampere). The transformers are: 1) very expensive (30%–40% of total system cost) 2) loss (50% of the total power losses) 3) bulky (40% of system real estate area and 90% of the system weight) 4) prone to failure. Moreover, the transformer-based UPFCs have poor dynamic response due to the six-step operation of each inverter bridge and large time constant of the transformers. Transformer saturation would even worse the control performance. Therefore, the conventional UPFC is not well suited for ultra-fast acting power flow control that is required in transmission of wind and solar power.

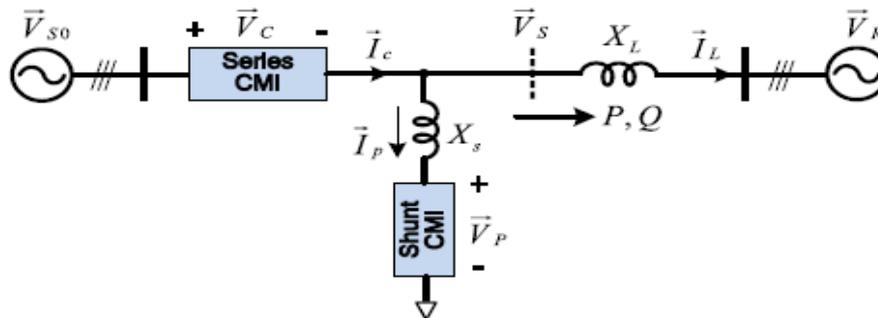


Fig.1. Configuration of transformer less UPFC

Hence, it is highly desirable to eliminate UPFC’s conventional and isolation transformers all together for widespread use of UPFC that is urgently needed for maximizing/optimizing energy transmission over the existing grids, increasing the grid transfer capability, enabling increased penetration of renewable power, and reducing transmission congestion.

II. OPERATION OF TRANSFORMERLESS UPFC

Unlike the conventional back-to-back dc coupling, transformer is not needed in the CMI-based UPFC. Hence, the new UPFC will be low in cost, light weight, small in size, high efficiency and fast dynamic response.2)The shunt inverter is connected after the series inverter, which is distinctively different from the traditional UPFC. Each CMI has its own dc capacitor to support dc voltage.3) There is no active power exchange between the two CMIs 4) The new UPFC uses modular CMIs and their inherent redundancy provides greater flexibility to system design and higher reliability.

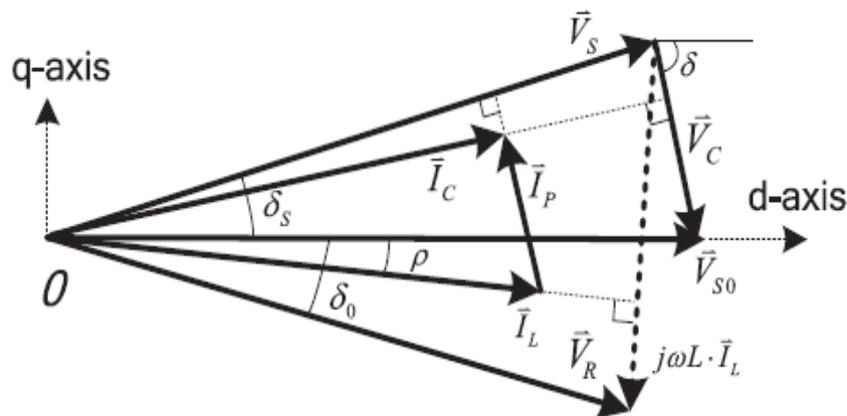


Fig.2. Phasor diagram to explain the transformer-less UPFC.

Due to the unique configuration, the basic operation principle of the transformer-less UPFC is different from conventional UPFC. Fig.1 shows a phasor-diagram explanation of principle of transformer-less UPFC operation, where \vec{V}_{so} and \vec{V}_r are the sending end and receiving end voltage, respectively. The series CMI is controlled to generate a desired voltage \vec{V}_c for obtaining the new sending-end voltage \vec{V}_s , which in turn, controls active and reactive power flows over the transmission line. The series CMI acts as a controlled voltage source. Meanwhile, the shunt CMI injects a current, \vec{I}_p to the new sending-end bus, \vec{V}_s to make zero active power into either CMI, i.e., to make the series CMI current, \vec{I}_c and the shunt CMI current, \vec{I}_p be perpendicular to their voltages, \vec{V}_c and \vec{V}_s , respectively.[3] As a result, no active power exchange to either CMI can be achieved and thereby makes the CMI possible for the utilization in the proposed transformer-less UPFC. The detailed operating principle of the transformer-less UPFC can be formulated as follows. The series CMI, P_{se} can be expressed by

$$P_{series} = \vec{V}_c \cdot \vec{I}_c \tag{1}$$

and the active power flow into the shunt CMI, P_{shunt} is

$$\begin{aligned} P_{shunt} &= \vec{V}_s \cdot \vec{I}_p \\ &= (\vec{V}_{so} - \vec{V}_c) \cdot (\vec{I}_c - \vec{I}_L) \\ &= \vec{V}_{so} \vec{I}_c \cos (90^\circ - \delta) - \vec{V}_{so} \vec{I}_L \cos \rho + \vec{V}_c \vec{I}_L \cos (\delta - \rho) \end{aligned} \tag{2}$$

where

\vec{V}_c is the voltage generated from the series CMI of the UPFC. \vec{V}_{so} is the old sending-end voltage phasor, and \vec{V}_s is the new sending-end voltage phasor after the UPFC. Thus the active power is not allowed to flow to both the series and shunt CMIs[4]. Hence

$$\begin{aligned} P_{series} &= 0 \\ P_{shunt} &= 0 \end{aligned} \tag{3}$$

Substituting P_{series} and P_{shunt} in (3) into (1) and (2), then the series CMI current I_C can be derived as

$$\vec{I}_c = \frac{\vec{V}_{so} \vec{I}_L \cos \rho - \vec{V}_c \vec{I}_L \cos(\delta - \rho)}{\vec{V}_{so} \sin \delta} \angle (90^\circ - \delta) \tag{4}$$

Since the current \vec{I}_L over the transmission line can be calculated according to a commanded power flow, the shunt CMI current \vec{I}_p can be consequentially calculated as

$$\vec{I}_p = \vec{I}_c - \vec{I}_L \tag{5}$$

In summary, the command for the series CMI is the desired voltage phasor \vec{V}_c for controlling power flow over the line according to a power flow command and the command for the shunt CMI is \vec{I}_p , which can be calculated from (4) and (5). As a result, the new transformer-less UPFC has the same functionality as the conventional UPFC.

CONTROL TECHNIQUE FOR SHUNT COMPENSATION:

From (6) the following control technique is used for the control of STATCOM. The control block diagram is shown in Fig.2. The unit signals $\sin(\omega t)$ and $\cos(\omega t)$ are generated using three phase supply voltage (V_a, V_b, V_c). The converter currents (I_a, I_b, I_c) are transformed to the synchronous rotating reference frame using the unit signals. The switching frequency ripple in the converter current components is eliminated using a low pass filter. The controller generates the reference voltages. The inverter supplies the desired reactive current and draws required active current to regulate total dc-link voltage $V_{dc1} + V_{dc2}$. The additional control is required to regulate individual dc-link voltages of the inverters. The resulting voltage of the cascaded converter can be given as $e_1 \angle \delta$, where $e_1 = \sqrt{e_d^2 + e_q^2}$ and $\delta = \tan^{-1}\{e_q / e_d\}$. The active power transfer between the source and inverter depends on δ and is usually small in the inverters supplying var to the grid. Hence δ , can be assumed to be proportional to e_q . Therefore, the q-axis reference voltage component of inverter-2 e_{q2}^* is derived to control the dc-link voltage of inverter-2 as

$$e_{q2}^* = (V_{dc2}^* - V_{dc2}) \left(k_{p4} + \frac{k_{i4}}{s} \right) \tag{6}$$

The q-axis reference voltage component of inverter-1 e_{q1}^* is obtained as

$$e_{q1}^* = e_q^* - e_{q2}^* \tag{7}$$

The dc-link voltage of inverter-2 V_{dc2} is controlled at 0.366 times the dc-link voltage of inverter-1 V_{dc1} . It results in four-level operation in the output voltage and improves the harmonic spectrum. Expressing dc-link voltages of inverter-1 and inverter-2 in terms of total dc-link voltage V_{dc} as

$$V_{dc1} = 0.732 V_{dc} \tag{8}$$

$$V_{dc2} = 0.268 V_{dc} \tag{9}$$

Since the dc-link voltages of the two inverters are regulated, the reference -axis voltage component e_d^* is divided in between the two inverters in proportion to their respective dc-link voltage as

$$e_{d1}^* = 0.732 e_d^* \tag{10}$$

$$e_{d2}^* = 0.268 e_d^* \tag{11}$$

The negative-sequence reference voltage components of the inverter e_{dn}^* and e_{qn}^* are controlled similar to positive-sequence components in the negative synchronous rotating frame as

$$e_{dn}^* = -x_3 - (\omega L) i_{qn} + v_{dn} \tag{12}$$

$$e_{qn}^* = -x_4 - (\omega L) i_{dn} + v_{qn} \tag{13}$$

Where v_{dn} and v_{qn} are d- q axes negative-sequence voltage components of the supply i_{dn} and i_{qn} are d-q axes negative-sequence current components of the inverter, respectively. The control parameters x_3 and x_4 are controlled as follows:

$$x_3 = \left(k_{p2} + \frac{k_{i2}}{s} \right) (i_{dn}^* - i_{dn}) \tag{14}$$

$$x_4 = \left(k_{p3} + \frac{k_{i3}}{s} \right) (i_{qn}^* - i_{qn}) \tag{15}$$

The reference values for negative-sequence current components and are set at zero to block negative-sequence current from flowing through the inverter.

CONTROL STRATEGY FOR SERIES COMPENSATION:

Fig.3. illustrates the control scheme employs in series compensation to produce the switching signal. The three phase grid voltages with supply voltage (400V) magnitude and with 120 degree phase shift with each other is compared with the load voltages. The signal obtained is used to produce the switching signals with the help of relay system i.e the signal is produced until its value is lower the actual rate. The inverted signals are produced to the remaining three switches.

$$V_{ga} = V_L \sin(\omega t) \tag{11}$$

$$V_{gb} = V_L \sin(\omega t - (2\pi/3)) \tag{12}$$

$$V_{gc} = V_L \sin(\omega t + (2\pi/3)) \tag{13}$$

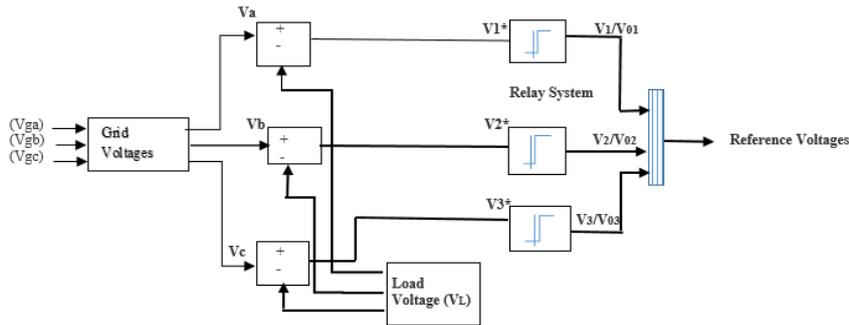


Fig.3.Control Strategy for series controller

Where V_1, V_2 and V_3 will be the switching signals for upper arm inverter 1&2 whereas V_{01}, V_{02} and V_{03} are the inverted signals which will be the switching pulses for the lower arm of inverter 1&2.

III. SIMULATION RESULTS

Fig.4 is the overall simulation diagram of Unified Power Flow Control, the modification is done thus the reactive power compensation is done in both shunt and series. In order to validate the performance of the system with UPFC, the model is designed with the source modeling in MATLAB/Simulink and the experimental waveforms are obtained.

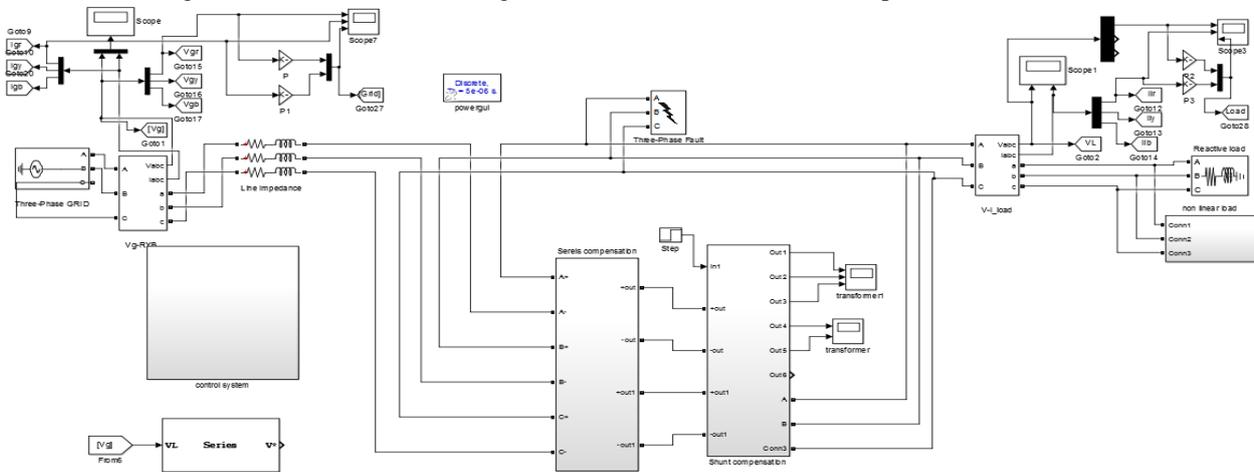


Fig.4:Transformer-less UPFC simulation diagram

Table .1.Specification of shunt control Simulink

S.NO	PARAMETERS	SPECIFICATION
1	Source voltage	400V
2	Supply frequency	50Hz
3	Inverter 1 DC link voltage	659V
4	Inverter 2 DC link voltage	241V

5	Carrier frequency	20Khz
7	Rated power	5 MVA
8	Equivalent line inductance X_s	0.12 p.u
9	Equivalent line inductance X_L	0.36.p.u
10	DC capacitance of each CMI	12000 μ F
11	Nominal series and shunt CMI Vdc	1000V

The shunt control is by cascaded multilevel inverter based STATCOM, which will regulate the current. For a 3 ϕ ,400V,50Hz AC line with a reactive and harmonic load the MATLAB simulation is done and the analysis is done. For analysis the compensation is come into operation at t=0.15s, by breaker arrangement with a step input. SPWM signals generate the switching pulses for inverter 1 and inverter 2 of the cascaded multilevel inverter.

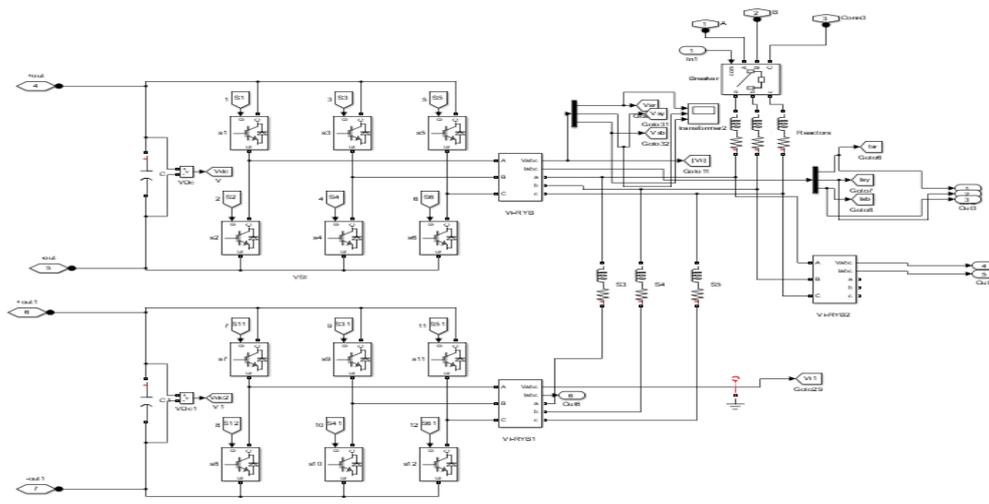


Fig.5: Simulation diagram for shunt compensation

In case of conventional UPFC the LV side is connected to the output of inverter and HV side connected to the transmission line whereas in transformer-less UPFC the output of the inverter 1 is connected to the inverter 2 through RL branch then it is connected to the transmission line through a series RL branch. These switches are triggered by the above mentioned schemes. The inverter 1 DC link is 659V and inverter 2 DC link voltage is 241V. The total DC link voltage is maintained with respect to its reference values for smooth operation.

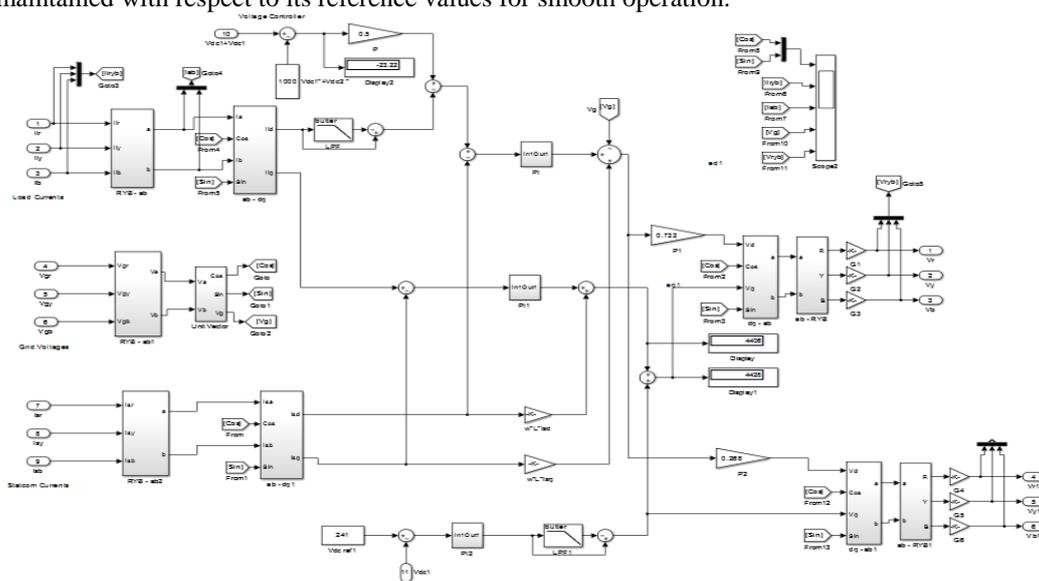


Fig.6:Control Technique simulation Diagram.

The method is analyzed in MATLAB for various operating conditions, the switching pulse are produced by sinusoidal pulse width modulation technique. The results of the switching signal for the respective carrier and reference wave is shown in figure.8 as it is seen from the control scheme which is employed for statcom the necessary for the conversion of three phase quantity into two phase.it is done through park transformation(synchronous reference frame).

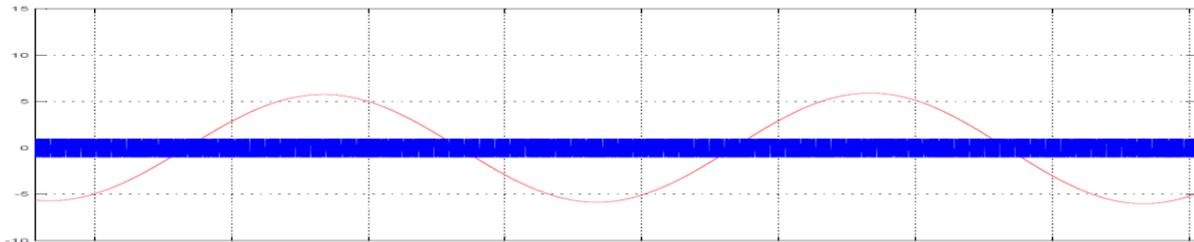


Fig.7: Reference sine waves and carrier triangular signal

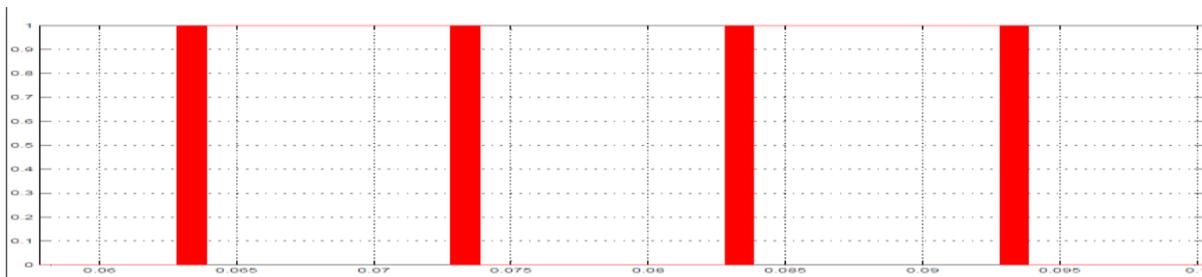


Fig8. SPWM output

The transformation is used to convert grid voltages, statcom currents and for load currents. Fig.10 shows the simulated result of d-q transformed signal from the three phase signal with the help of unit signals. It can be seen that the quadrature axis current leads the direct axis current by 90 degrees.

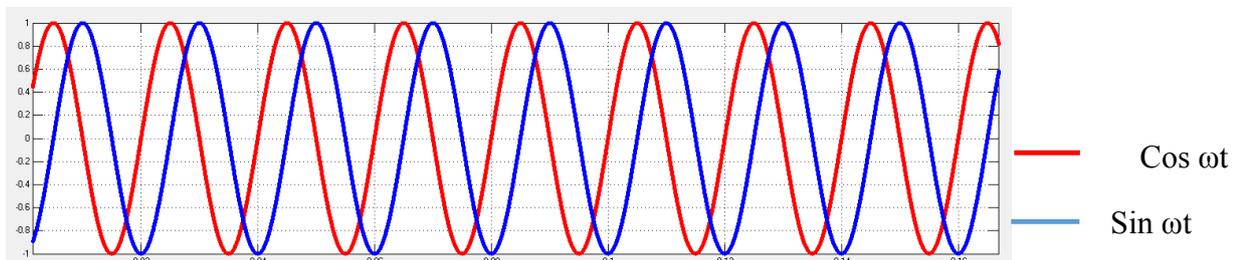


Fig.9:Unit signals output

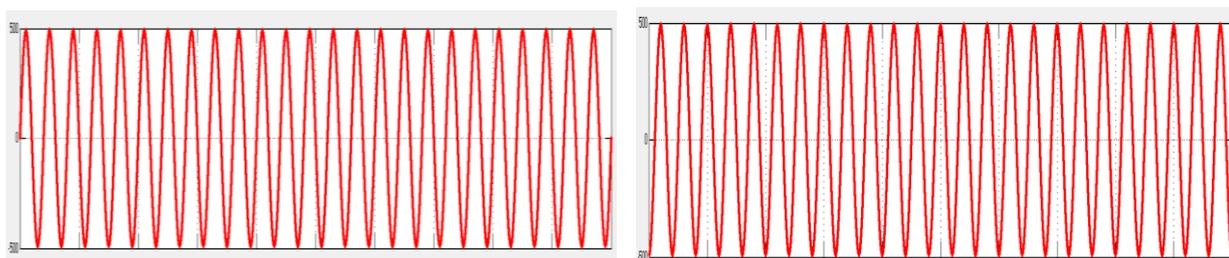


Fig.10: d-axis & q-axis component waveform after transformation

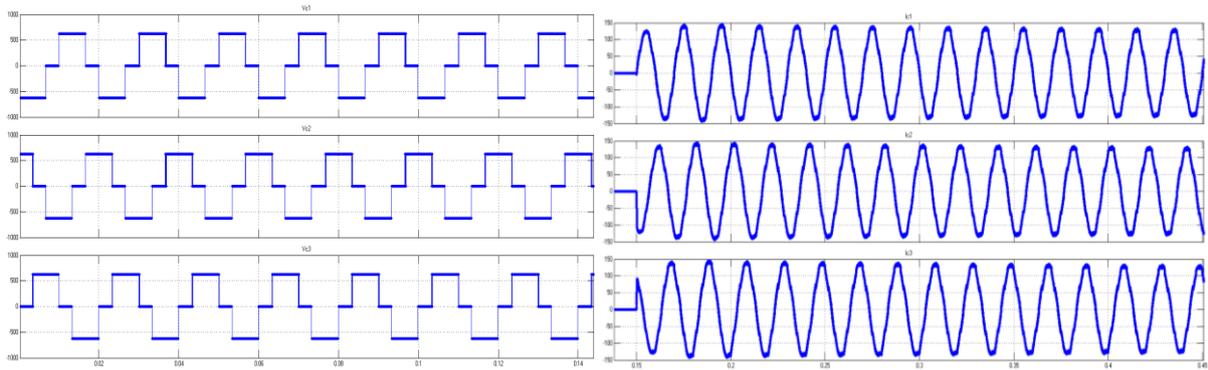


Fig.11: Inverter output voltage and current waveform

Loads that are used for analyzing the performance are non-linear load and reactive load (capacitive or inductive) with 5MVA capacity. For linear load the operation is checked for capacitive current lead and lag. For nonlinear load it is observed that the current and voltage are non-sinusoidal. Since for series connected the input to the transmission lines is connected through linear transformer (1:1 ratio), the LV side of linear transformer is connected to the output of inverter and HV side connected to the transmission line whereas in shunt connected the output of the inverter 1 is connected to the inverter 2, through RL branch then it is connected to the transmission line through a series RL branch.

As stated before the total DC link voltage will be $V_{dc1} + V_{dc2}$ (i.e., $653 + 347 = 1000v$). the following diagram shows the dc link maintained at 1111V throughout the operation

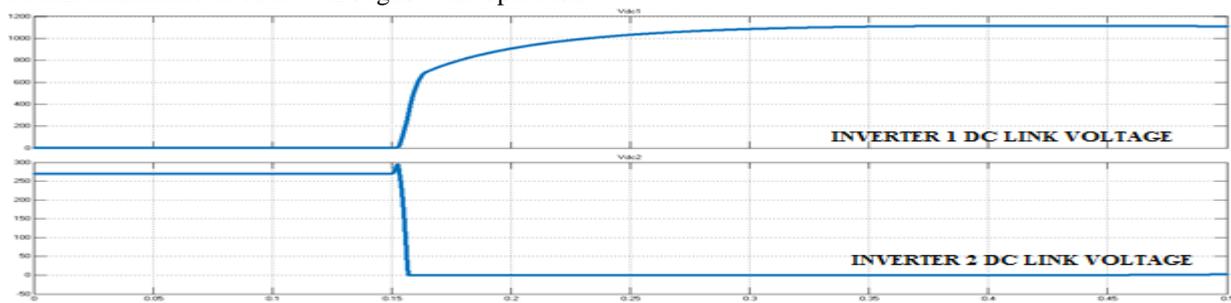


Fig.12.DC link voltage control

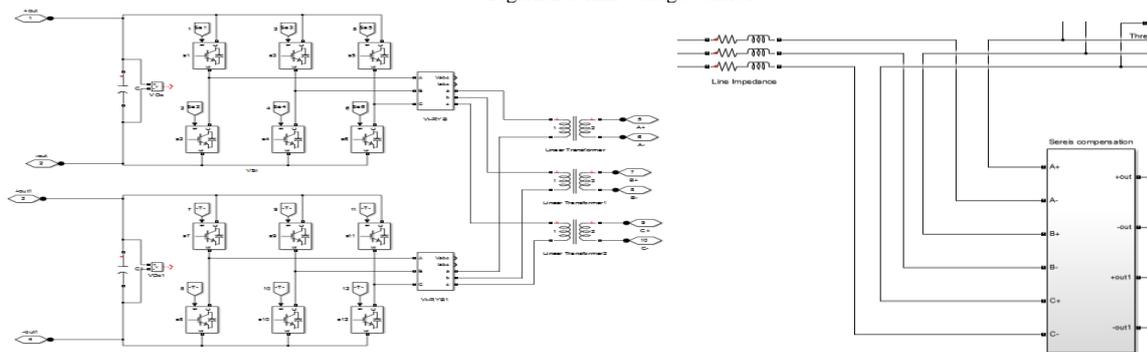
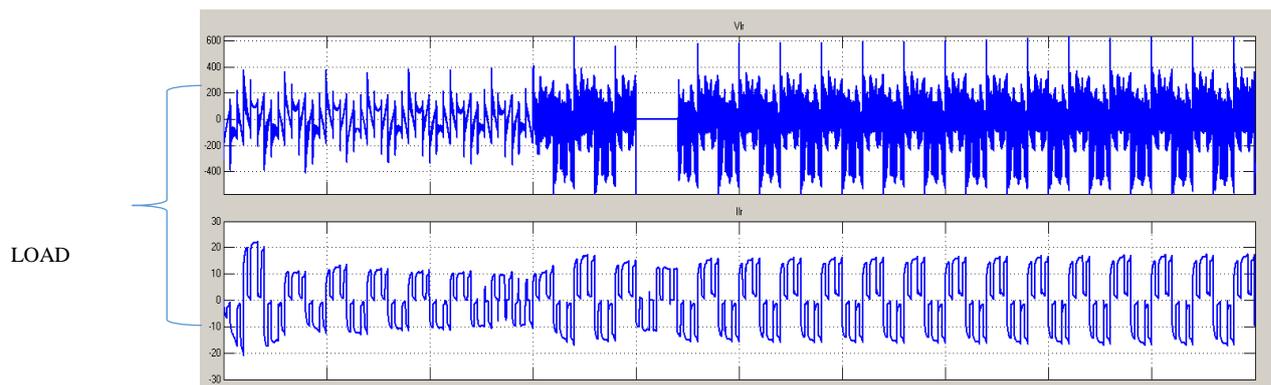


Fig.13a) cascaded SSSC simulation block b) SSSC to grid



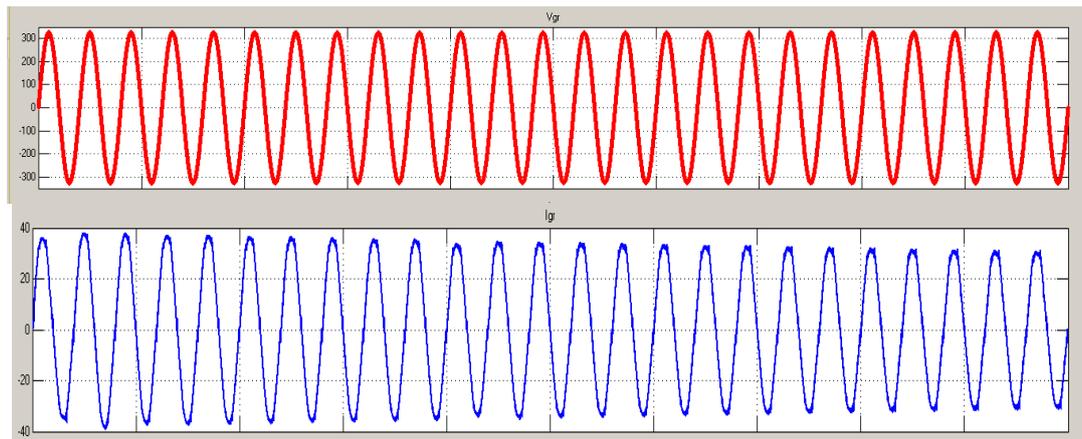


Fig.14.voltage and current waveform of compensated load and source voltages

IV. CONCLUSION

Reactive power compensation is done in both shunt and series without transformer connection. In order to validate the performance of the system with transformer-less UPFC, the model is designed with the source modeling in MATLAB/Simulink and the experimental waveforms are obtained. The performance of the transformer-less UPFC is studied under steady state condition. Voltage and current is compensated by the face to face connection of series and shunt compensating devices. DC-link voltage balance is one of the major issues in cascaded inverter-based transformer less UPFC. The DC link voltage is maintained at a constant value throughout the operation at various load condition. The new UPFC consisting of two CMIs offers several advantages over the traditional UPFC, such as completely transformer-less and highly modular structure, light weight, high efficiency, high reliability, low cost, and fast dynamic response. The new transformer-less UPFC is, therefore, very well suited for fast. By the comparison of both the conventional and transformer-less UPFC the later has the advantage of lower voltage total harmonic distortion.

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