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RENEWABLE ENERGY SOURCES BASED STATIC COMPENSATOR (STATCOM) FOR POWER QUALITY IMPROVEMENT

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Abstract:

This paper presents an operation of hybrid photovoltaic (PV) and Wind system (W) based DSTATCOM for significant energy conservation, harmonic mitigation and reactive power compensation. When the PV system generates excessive or equal power required to the load demand, then the coordinating logic disconnects the service grid from the load and with a consequent reduction of panel tariff and global warming gasses. The PV module is connected to the DC side of DSTATCOM through the DC–DC converter. Converter switch is controlled by fuzzy-based perturb & observe (P&O) maximum power point tracking (MPPT) algorithm and it eliminates the drawback in the conventional PV system. The reference currents are extracted by the fuzzy logic controller based control strategy. This proposed PVW- DSTATCOM, if connected at the terminals of a small industry or a home or a small enlightening institution can avoid the use of interruptible power supply and individual stabilizer. An emulation using MATLAB Simulink is presented to validate the advantage of the proposed system.

Key Words: DSTATCOM - Distribution Static Compensator, T - Connected Transformer, Boost Converter & Harmonic Reduction

1. Introduction:

In current scenario researchers have interest on renewable energy based power quality enhancement in the power system because of extensive use of non-linear electronic Loads [1]. The usage of fossil fuels causes global warming whose objectionable effects and also insufficient on globe. For a viable world the usage of fossil fuels must be decreased, in fact ended. As an alternative, the usage of renewable energy sources must be increased because it does not cause greenhouse effect in contrary to the fossil fuels. It is sensible that a solar system can provide an uninterrupted supply of energy due to cyclical variations. The Photovoltaic arrangement has the ability to acquaintance it in sequence to offer the essential dc voltage. The generated power from the Photovoltaic arrangement requires power condition equipment before connecting it to the dc link [2, 3]. Thus the DC-DC boost converter is used to build up the voltage level. The three-phase four-wire (3P4W) distribution system did not employ to distribute the electric power single phase nor do three phase loads in residential, commercial and industrial buildings. For single phase loads supply is provide between one of the phase conductors to neutral wires and these loads are not balanced, as a result net current flowing through the neutral conductor and initiate harmonics. It's not only the source for neutral current and also the usage of nonlinear loads such as Power electronic converters; Adjustable speed drives, uninterruptable power supplies etc. are the liable factor for the power quality issues. The power quality at the distribution system is governed by various standards such as IEEE-519 standard [4].

The investigation to power quality problems are reported in the literature and are known by the universal name of custom power devices (CPD). These custom power devices include the DSTATCOM (distribution static compensator), DVR (dynamic voltage restorer), SAF (Shunt Active Filter) and UPQC (unified power quality conditioner). The SAF is a parallel linked device which focuses the power quality problems. Some of the topologies of shunt active filter interface with three-phase four-wire system for the mitigation of neutral current and power quality compensation. Four-leg voltage source converter (VSC), three single-phase VSCs, three-leg VSC with split capacitors, three-leg VSC with zigzag transformer, and three-leg VSC with neutral terminal at the positive or negative of dc bus [5,6]. The voltage regulation in the distribution feeder is improved by installing a shunt compensator. There are various schemes stated in the literature for control of SAF such as synchronous reference frame theory, IcosΦ algorithm, and instantaneous reactive power theory, hysteresis bang-bang compensation, etc. [7]. The synchronous reference frame theory is used for the control of the proposed shunt active filter.

In this paper, a new methodology of SAF grid interfaced T-connected transformer is proposed for the three-phase four wire distribution system [8, 9]. T-connected transformer offer current cancellation at neutral conductor and mitigates the harmonics, the SAF interfaced boost converter compensates the source harmonic neutral current, load reactive power, and balances load. The IGBT based VSC is self-supported with a dc bus capacitor and is controlled for the required compensation of the load current. The shunt active filter is designed and simulated using MATLAB software with its Simulink and power system block set (PSB) toolboxes for source harmonic neutral current compensation, THD (Total Harmonic Distortion) reduction and reactive power compensation at nonlinear loads.

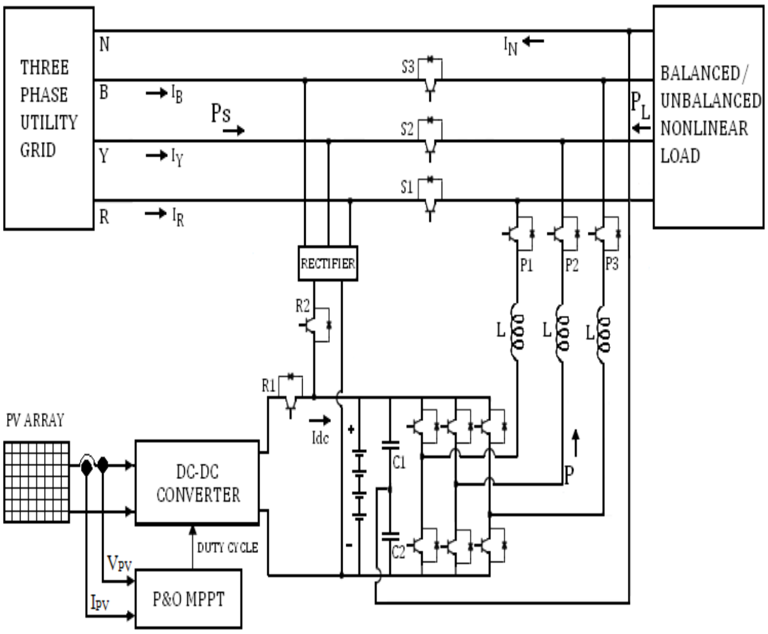

Figure 1: Schematic diagram of proposed PV-DSTATCO

2. System Configuration and Design:

The boost converter interfaced four-leg VSC with T connected transformer is coupled at point of common coupling (PCC) with nonlinear load is shown in Fig. 1. The VSC has an inductors, insulated-gate bipolar transistors (IGBTs) and dc capacitors. The dc bus voltage of VSC generally depends on the instantaneous energy available to the shunt active filter [10]. The dc bus voltage is designed as, (1) Where VLL is the ac line voltage of SAF and m is the modulation index, consider VLL of 415 V and modulation index is 1. Then, Vdc is obtained as 678V and is preferred as 700V. The dc capacitor

(Cdc) of VSC designed with related to the instantaneous energy present in the SAF during transient conditions [10]. The dc capacitor is designed as, (2) Where Vdc1 is the least voltage of dc link capacitor and Vdc is the reference voltage of dc link capacitor, V is the phase voltage, a is the overloading factor, I is the phase current and t is time required for dc link capacitor recovery. During transient condition Consider, a 1.5% of in dc link capacitor decreased, Vdc = 700 V, Vdc1 = 690 V, V = 239.60 V, a = 1.2, I = 28.76 A, t = 350 μs, the designed value of Cdc is 1228 μF and is chosen as 1500 μF. The value of AC inductor of VSC depends on, dc bus voltage (Vdc), the current ripple (Icr) and switching frequency fs and Lf is given as [10]

Consider, peak to peak current ripple Icr p-p is 5%, dc bus voltage Vdc is 700 V, m is modulation index is 1, a is the overloading factor 1.2 and switching frequency fs is 10 KHz the designed value of Lf to be 0.421mH A low-pass filter is regulated at half the switching frequency to filter the high frequency noise at the PCC. A low impedance of 8.1 Ω is taken into the consideration for a frequency of 5 kHz, the ripple filter has series resistance (Rf) of 5 Ω is included in series with the capacitor (Cf) as 5 μF. A. The impedance is 637 Ω at 50Hz frequency, which is adequately large and the ripple filter has negligible fundamental current.

A Design of the T-connected Transformer Figure: T-connected transformer (b) Pharos diagram A three-phase four-wire grid interfaced T-connected transformer has two single phase transformer in T-configuration, connection and phasor diagram as shown in Fig. 2a and b. The T-connected transformer provides neutral current cancellation and zero-sequence fundamental harmonic current when it's connected in parallel to PCC. The zero-sequence fundamental current is split into three currents and flow through the windings of the transformer during unbalanced load conditions. The current rating of the windings is decided by the required neutral current compensation. Turn's ratio of the transformer windings decides the voltage range across each winding. Consider Va is the resultant voltage and Va1 & Vb1 are the voltages across each winding then (4) (5) Where K1 and K2 are the winding fractions in the phases. For the instant |Va | = |Vb | = V then the voltages across Va1 is equal to Va cos 30◦ and Vb1 is equal to Va sin 30◦. From equation (4) and (5), the winding fractions K1 = 0.866 and K2 = 0.5. Consider the line voltage is Vca = 415 V, then Va=Vb=Vc = 415 √3= 239.60 V (6) Va1 = 207.49 V, Vb1 = 119.80 V (7) From the equation, ratings of the transformer are chosen 5kVA, 240V/120V/120V and 5kVA, 208V/208V.

3. System Modeling and Control:

A simple PV cell is essentially an ideal current source in parallel with an ideal diode. The current source represents the current generated by the PV cell due to the photons received by it. PV cells have nonlinear characteristics which vary with radiation intensity and temperature. PV cells produce sufficient power if connected in series. The single-diode equivalent circuit of a PV cell as show in Figure. The circuit is composed of a current source, a diode, series, and parallel resistance. Solar irradiation level will change due to the weather fluctuations in Tamilnadu [11] as shown in Table 1. From the table, it is observed that the Solar irradiation may vary between 5.03 - 5.16 Kwh/m2/day. Fig. 3. Single diode equivalent circuit of a real PV cell

Table I: Solar irradiation in Tamilnadu Kwh/m2/day onto a horizontal surface (April 2013).

Summary	AirTemp.(o C)		Relative Humidity (%)	Wind Speed (kmph)	Soil Moisture 15 cm (%)	Soil Temp. 15 cm (o C)	Rainfall (mm)	Solar Radiation (cal/cm2)	Atmospheric Pressure (hpa)	Leaf Wetness (hr)
	Maximum	Minimum								
01-04-2013 08:30:00	37.6	25.9	54.8	3.4	10.1	34.5	0.0	264.7	977.9	0.0
02-04-2013 08:30:00	37.5	25.6	54.9	2.9	10.1	34.5	0.0	92.5	978.7	0.0
03-04-2013 08:30:00	37.6	26.8	60.1	4.1	10.1	34.6	0.0	361.2	978.9	0.0
04-04-2013 08:30:00	35.6	25.9	64.8	2.7	10.1	34.2	0.0	402.1	979.0	0.0
05-04-2013 08:30:00	39.1	26.3	64.3	2.6	10.1	34.1	4.0	506.7	977.3	0.6
06-04-2013 08:30:00	38.5	27.7	55.1	3.3	10.2	33.6	0.0	371.5	976.9	0.0
07-04-2013 08:30:00	38.2	28.6	56.4	2.7	10.2	33.8	0.0	371.2	976.1	0.0
08-04-2013 08:30:00	36.8	25.7	63.5	3.5	10.2	33.6	0.0	101.9	976.5	0.8
09-04-2013 08:30:00	37.3	26.6	57.4	3.1	10.2	33.7	0.0	306.8	977.3	0.0
10-04-2013 08:30:00	37.7	26.1	52.5	3.1	10.1	34.1	0.0	0.0	978.3	0.0
11-04-2013 08:30:00	38.9	25.4	50.9	3.5	10.1	34.3	0.0	58.5	978.0	0.0
12-04-2013 08:30:00	38.1	26.2	55.4	3.3	10.1	34.7	0.0	0.0	977.5	0.0
13-04-2013 08:30:00	38.5	25.2	53.3	4.7	10.1	34.9	0.0	6.5	978.6	0.0
14-04-2013 08:30:00	37.6	26.7	56.7	3.2	10.1	34.9	0.0	131.6	979.9	0.0
15-04-2013 08:30:00	38.6	27.6	58.7	3.3	10.1	35.2	0.0	255.1	978.9	0.0
16-04-2013 08:30:00	38.2	25.0	67.2	3.1	10.1	34.7	3.5	211.8	978.1	3.7
17-04-2013 08:30:00	38.6	27.8	55.9	2.6	10.2	33.5	0.0	478.2	976.4	0.0
18-04-2013 08:30:00	38.6	27.3	57.7	3.1	10.2	34.0	0.5	468.5	975.5	1.6
19-04-2013 08:30:00	37.5	26.4	59.7	3.4	10.2	33.7	0.0	438.4	976.8	0.1
20-04-2013 08:30:00	38.7	25.5	50.9	3.0	10.2	34.2	0.0	474.4	976.2	0.0
21-04-2013 08:30:00	38.2	25.7	52.3	2.9	10.1	34.8	0.0	522.8	976.7	0.0
22-04-2013 08:30:00	38.4	26.3	55.6	3.5	10.1	35.1	0.0	408.9	977.1	0.0
23-04-2013 08:30:00	38.4	26.9	55.2	4.1	10.1	35.4	0.0	390.3	978.4	0.0
24-04-2013 08:30:00	37.0	27.8	56.5	3.1	10.0	35.2	0.0	422.8	980.0	0.0
25-04-2013 08:30:00	35.0	25.9	69.1	2.0	10.1	33.6	0.0	12.0	980.5	0.8
26-04-2013 08:30:00	36.2	27.1	64.7	2.8	10.1	33.9	0.0	367.2	980.0	0.0
27-04-2013 08:30:00	37.6	26.7	61.1	3.7	10.1	34.4	0.0	434.2	979.6	0.0
28-04-2013 08:30:00	37.2	27.6	59.7	2.6	10.1	34.6	0.0	415.0	978.7	0.0
29-04-2013 08:30:00	40.2	26.9	49.3	2.4	10.1	35.0	0.0	465.5	976.8	0.0
30-04-2013 08:30:00	39.0	26.2	61.8	2.7	10.2	34.2	5.0	461.9	976.9	0.5
Month Average	**37.9**	**26.5**	**57.8**	**3.1**	**10.1**	**34.4**	**0.4**	**306.7**	**977.9**	**0.3**

Table II: Parameters of CANADIAN SOLAR CS5P-220M panel.

Parameters	Symbol	Typical Value
Nominal Power	Pmax	220 W
Open Circuit Voltage	Voc	58.8 V
Short Circuit Current	Isc	5.01 A
Temp. Coefficient of Power	kt	0.45%/K
Temp. Coefficient of Voltage	kv	0.206V/K
Maximum Power Voltage	Vmpp	47 Volts
Maximum Power Current	Impp	4.68 Amps
Number of Cells	-	96 (8 x 12)
Power per unit of area	-	12.0W/ft2 (129.4W/m2)

To represent the Photovoltaic part in Where A is curve fitting constant, k is the Boltzmann constant (1.381X10-23 J/K), T is the junction temperature in kelvin (K). Ig is the generated current in photovoltaic module (A) under short circuit condition, Id is the current shunted through the intrinsic diode, Vpv is the Terminal voltage of the cell, Rs ans RP are Series, shunt Resistance computed from I-V characteristics. I-V characteristics CANADIANSOLAR CS5P-220M solar panel. Based on the fluctuation in the solar irradiation the proposed methodology has split into three operations. First one, during bright illumination; the photovoltaic arrangement can directly link to the boost converter to increase the voltage and match the dc link voltage. In this case the battery is not charge. Second one, during excess power, the output voltage of the photovoltaic arrangement drive the boost converter coupled SAF for compensating the source current. In this case the battery is charging. Third one, during dark illumination, the photovoltaic output is absent and the battery has only provision for providing compensation.

The circuit operation is divided into two modes. In mode 1, when the switch is in on condition the input current supplies energy to the inductor for a period Ton. Similarly in mode 2, when the switch is off, the inductor voltage adds to the source voltage and current is forced to flow through diode D and the load for a period Toff. The PV or battery voltage of 47 V is fed to the boost converter and the output voltage of the boost converter of 676 V is obtained to maintain the dc link voltage of the four-leg voltage source converter. In order to step-up the voltage, a switching frequency of 25 kHz is considered and the inductorvalue of 0.0191 mH is calculated [14]. The capacitor C of 1500 μF is chosen as per Eq. (2). The output voltage Vout is greater than the input Voltage Vin and the output equation is shown in the following equation. (11) Where V is the PV or battery voltage, D the duty cycle, Ton the on time, and Toff the off time.

4. Control of DSTATCOM:

MATLAB–SIMULINK, Table 2 shows the CANADIAN SOLAR CS5P-220M datasheet, parameters are obtained at temperature of 25 0C and solar irradiance of 1000 W/m2. The Photovoltaic components obtain a 47 V voltage and also propose more energy than conventional solar cells [12 The I–V characteristics of Photovoltaic component at constant temperature of 250C with variable solar irradiance. The Photovoltaic representation is developed using essential equations of photovoltaic cells as well as the effects of temperature and solar irradiation [13]. The diode and load current equations are given as, (8) (9) The highest photovoltaic voltage is obtained under open circuit situation, when IPV = 0 with negligible resistance is given as, The control scheme block diagram is shown in Fig. 6.Several control methodologies are available to generate reference current for three-phase four-wire system of SAF, synchronous reference frame theory (SRFT), IcosΦ algorithm, instantaneous reactive power theory, hysteresis bang-bang compensation, etc. [7]. The SRFT is used in this research for the control of SAF. The load currents (iLa,iLb, iLc), the PCC voltages (VSa , VSb , VSc), and dc bus voltage (Vdc) of SAF are sensed as feedback signals. The load currents from the a–b–c frame are first converted to the α–β–0 frame and then to the d–q–0 frame using the Park's transformation as in eqn. (12).

Where cos θ and sin θ are obtained using a three-phase phase-locked loop (PLL). A PLL signal is obtained from terminal voltages for generation of fundamental unit vectors for conversion of sensed currents to the d–q–o reference frame [15]. The SRF controller extracts dc quantities by a low-pass filter, and hence, the non-dc quantities are separated from the reference signal. The d-axis and q-axis currents consist of fundamental and harmonic components as (13) (14) The control strategy for reactive power compensation consider that the source must deliver the mean value of the direct-axis component of the load current along with the active power component current for maintaining the dc bus and meeting the losses (iloss) in Dstatcom. The output of the first proportional-integral (PI) controller at the dc bus voltage of is Dstatcom considered as the current (iloss) for meeting its losses (15) Where Vde(n) is the error between the reference voltage (Vdc*) and sensed dc voltages (Vdc(n)) at the nth sampling instant. Kpq and Kiq are the proportional and integral gains of the dc bus voltage PI controller. The reference source current is therefore (16) the reference source current must be in phase with the voltage at the PCC but with no zero-sequence component.

It is therefore obtained by the following reverse Park's transformation with id* as in (12) and iq* and i0* as zero Likewise, the amplitude of ac terminal voltage (VS) at the PCC is controlled to its reference voltage (VS*) using the PI controller. The output of

PI controller is considered as the reactive component of current (iqr) for zero voltage regulation of ac voltage at PCC. The amplitude of ac voltage (VS) at PCC is calculated from the ac voltages (Vsa, Vsb, Vsc) as (18) Then, a PI controller is used to regulate this voltage to a reference value as (19) Where Vte(n) = Vs* – VS(n) denotes the error between reference (VS*) and actual (VS(n)) terminal voltage amplitudes at the nth sampling instant. Kpq and Kiq are the proportional and integral gains of the dc bus voltage PI controller. The reference source quadrature-axis current is (20) The reference source current is obtained by reverse Park's transformation using with id* as in (equation no) and iq* as in (equation no) and i0* as zero. The gains of the controllers are obtained using the Ziegler-Nichols step response technique [29]. A step input of amplitude (U) is applied and the output response of the dc bus voltage is obtained for the open-loop system. The maximum gradient (G) and the point at which the line of maximum gradient crosses the time axis (T) are computed. The gains of the controller are computed using the following equations: (21) (22) In a current controller, the sensed and reference supply currents are compared and a proportional controller is used for amplifying current error in each phase before comparing with a triangular carrier signal to generate the gating signals for six IGBT switches of VSC of SAF. The gating signals for the fourth leg of VSC of the SAF are obtained from the error signal by comparing sensed (isn) and reference (isn*) Two PI controllers are used for the purpose of control of dc bus voltage of SAF and ac current at PCC. The compensation current should lead or lag by 90 degree from the voltage. The SAF draws a lagging current to reduce the line-voltage amplitude, when the load injects capacitive reactive power, when the load is an inductive; the SAF operates as a capacitor. Along with reactive current control, the control of SAF consists of the following control functions: harmonic elimination, load balancing and neutral current compensation.

5. Result and Discussion:

The boost converter fed four-leg VSC with the T connected transformer based SAF in a three-phase four-wire system which is modeled and simulated by using the MATLAB with its SIMULINK environment and PSB toolboxes. The source consists of three phase ac voltages with neutral and non-linear loads are connected at PCC. The SAF is coupled in parallel to the system through interfacing inductances. The electrical power system under nonlinear load condition for source voltage and source current without compensation is shown in Fig. 2a and Fig. 2b. The source current harmonic spectrum without compensation is shown in Fig. 2c with the terminal current THD as 20.80%. At 0.1 s, the load is changed to two phase load and also the load currents are absence between 0.2 s and 0.25 s. These loads are applied again at 0.25 s respectively. The neutral current without the compensation is shown in Fig. 3a. The source current is still sinusoidal even though the load changes occur is shown in Fig. 4a with the terminal current THD of 1.48%.The terminal voltage is maintained to the reference voltage by adjusting the reactive power injection is shown in Fig. 5a at 0.2 s the SAF is connected to the grid. It is also observed that the dc bus voltage of SAF is maintained at the reference value under all disturbances is shown in Fig. 6a.The electrical power system data used for simulation is given in Appendix A.

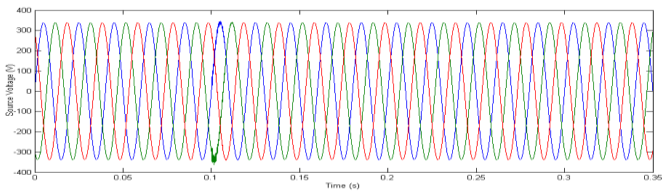

Figure 2a: Source voltage

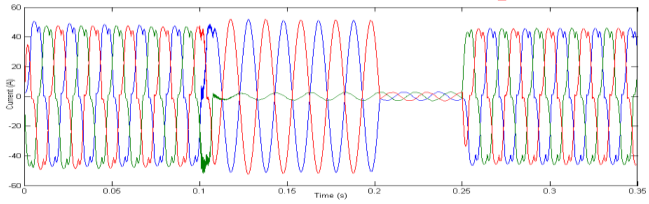

Figure 2b: Source current without compensation

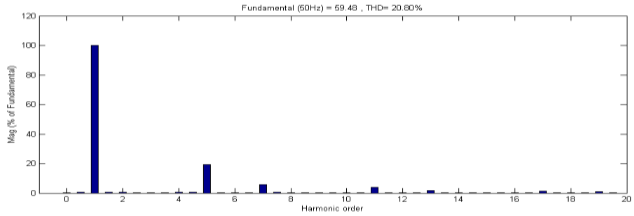

Figure 2c: Performance of phase A source current with its spectrum without compensation

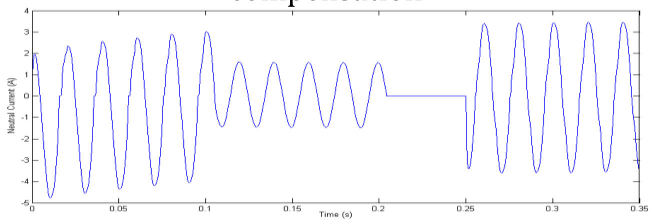

Figure 3a: Neutral current without compensation

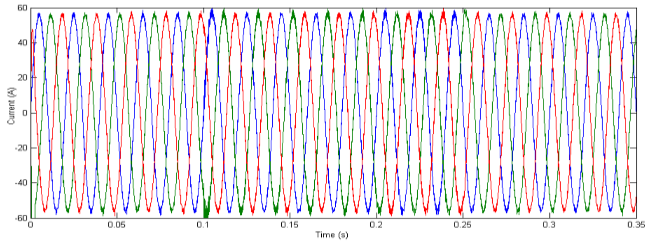

Figure 4a: Source current after compensation.

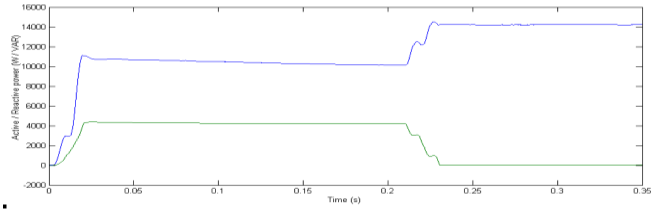

Figure 5a: Active and reactive power compensation.

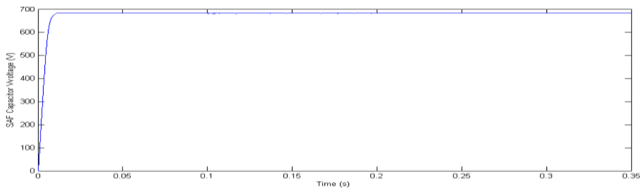

Figure 6a: Dc link capacitor voltage.

6. Conclusion:

The performance of a new topology of three-phase four-wire SAF consisting of PV or battery operated boost converter fed Four-leg VSC with a T-connected transformer has been demonstrated for reactive power compensation, harmonic elimination, and neutral current compensation in interconnected utilities. The T-connected transformer improves the transient stability of a power system and also observed that its helps in damping low frequency power oscillations. The total kilovolt-amperes rating of the T-connected transformer is lower than the Zigzag-delta transformers and star-delta transformers for reactive power compensation and also it's found that harmonic mitigation techniques using T-connected transformer are a viable choice for mitigating rich triplen harmonics in four-wire electrical distribution system. T-connected transformer is also significantly reduced neutral current flowing back to the system almost up to 90%. A synchronous reference frame method has been presented for reactive power compensation, source harmonic reduction, and neutral current compensation. The boost converter is used to step up the voltage to match the dc link voltage of the four-leg VSC It is observed that the THD (Total Harmonic Distortion) of the source current for phase A is reduced from 20.80 to 1.48

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