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An Active Line Conditioner to Balance Voltages in a Distributed Generation System

Yashit Tita[1st]
Assistant Professor, Electrical Engineering Department
Dr. Subhash Technical Campus,
Junagadh, Gujarat (India)

Bhavin Gondaliya[2nd]
Head, Electrical Engineering Department
Dr. Subhash Technical Campus,
Junagadh, Gujarat (India)

Abstract*: An active line conditioner is proposed to correct dynamically voltage unbalances in a three phase AC system. In this system it is shown that the injection of a correction voltage Vinj in one phase is sufficient to nullify the negative sequence voltage component in the incoming three phase supply. The resulting three phase voltages at the load terminals are essentially positive sequence voltages and hence are balanced. The dynamic cancellation of the negative sequence voltage component by the proposed scheme drastically improves the performance of induction motor loads connected to a weak ac system. A thorough analysis of the scheme along with the suitable design guides is presented. Simulation results for different operating conditions are also presented to illustrate the merit of the proposed technique. The presented, simulation results demonstrate the effectiveness of the control technique. The performance of proposed system is analyzed using simulations with MATLAB/SIMULINK 7.4.0 (R2007a)

Keywords: MATLAB, Simulation, Voltage, Vinj.

I. INTRODUCTION

Distributed Generation (DG) is increasing in nowadays power systems, mainly due to effective support schemes for renewable energy and cogeneration. Existing power systems may be or may not be suitable to include a certain amount of DG without harming the power system stability. Several high level studies analyzed the impacts of DG on the power system design and operation. In a three-phase power system the generated voltages are sinusoidal with the individual phases 120º apart. At the distribution end the unbalanced single phase loads and nonlinear loads cause unequal voltage drops in the transformer and line impedances. The result is an unbalanced supply voltage at the point of common coupling. In the power system, balanced conditions are normally maintained by distributing the load equally among the three phases. The single -phase loads on the system now vary continuously with larger hourly variations. The result is a continuously varying unbalanced load that leads to unbalanced voltage problems [1]. The effect of voltage unbalance is severe on induction motors and three-phase power electronic converters and drives [2]. These effects are explained in terms of the negative sequence component in the unbalanced voltages [3].

In induction motors the effect of voltage unbalance is to circulate large currents in the rotor and to reduce the available output torque. Often the result of unbalanced operations is burn-out of the machine windings due to overheating (normally the thermal characteristics of the motor due to a negative sequence voltages are not part of the overload protection). Measured rotor currents in induction motors operating with unbalanced voltages show that a 5% unbalance decreases the motor life to 30% [3]. The voltage unbalance problem is well known. IEC standards restrict the permissible voltage unbalance on induction motors to 1% [4] and require a rerating of the machines if unbalance is greater. However, ANSI and IEEE do not have a limit as of today [4]. Based on recent studies conducted independently by ANSI, NEMA, and IEC the proposed limits on unbalance are [4].

Several power electronic solutions to the unbalanced voltage problem are reported in the literature. However, these approaches employ active correction stages in each phase of the three phase supply. The resulting balancing system is complex, high in component count and difficult to control. In this thesis the voltage balancing function is achieved by injecting a voltage in only one phase and in only two phases, if the load is very sensitive to the voltage amplitude [5]. The need for renewable power generation and describes a medium-power Autonomous Renewable Energy Conversion System (ARECS), integrating conversion of wind and solar energy sources. The maximum energy transfer of the wind energy is assured by a simple and reliable control strategy adjusting the stator frequency of the IG so that the power drawn is equal to the peak power production of the wind turbine at any wind speed. For improving the total system efficiency, high efficiency converters have been designed and implemented [6]. The advantages of a self-excited three phase induction generator (SEIG), which is, it requires less maintenance compared to other conventional electrical generators. In the application of SEIG, voltage and frequency may be regulated by using a proper power electronic device. A solid-state controller for regulating output voltage of a three-phase SEIG is designed and implemented [7].

The propose a new scheme to connect wind turbines to the power grid. This scheme helps in limiting the fault currents as well as in voltage unbalance compensation. Voltage is injected in series with the transmission line to limit the fault currents as well as to balance the voltages. This scheme allows wind turbines to remain synchronized to the grid during faults or during low voltages and is useful for doubly fed as well as squirrel cage induction generators [8]. The proposes a new series compensated induction generator/battery supply topology which provides a constant voltage and frequency at the terminals, allowing minimum current harmonic distortion while at the same time providing a source and sink of real and reactive power. With appropriate control of the reactive power, the speed of the generator is allowed to vary within a relatively wide range. This technique can be further expanded by applying AC capacitors in parallel with the load to lessen the burden of the PWM inverter [9]. The deal with the design of static compensator (STATCOM) based voltage regulator for self-excited induction generators (SEIGs). The required reactive power can be provided by a STATCOM consisting of ac inductors, a dc bus capacitor, and solid- state self-commutating devices. Selection and ratings of these components are quite important for design and control of STATCOM to regulate the terminal voltage of SEIG. The analysis, design, and selection of these STATCOM components are presented for five different rating machines to operate at varying power factor loads [10].

An active power filters (APF) to eliminate harmonics and to compensate reactive power and neutral current of three-phase four-wire symmetrical and unbalanced nonlinear loads. A set of three single-phase insulated-gate bipolar transistors (IGBT)-based voltage source inverter (VSI) bridges with a common DC bus capacitor is used as the APF. A sliding mode controller (SMC) over the average DC bus voltage is used for the control. A hysteresis rule based carrier less pulse width modulation (PWM) current control is employed to generate the gating signals to the switching devices. A set of three single-phase diode bridge rectifiers with capacitive-resistive loading is used for nonlinear loading [11].

II. Operation of Active Power Filter

A. When load is normal:

The connection of the proposed Active Line Conditioner is shown in Fig. 1. In the controller the phase voltages are used to generate a control voltage Vneg proportional and in phase with the desired Vinj (if the neutral is not available a fictitious neutral can be generated and used as only the relative phase angles are required). This Vneg is input to the PWM generator unit of the Line Conditioner. The PWM gating signals are generated by using a sine-triangle intersection method, using the obtained control voltage Vneg as the modulating voltage. The frequency of the carrier is chosen to be high. An LC filter aids in filtering switching frequency harmonics in the primary side of the series transformer. The dc bus could be a dc generator, a battery source or it could be obtained by rectifying the ac supply. For normal applications requiring voltage boost the dc source could be a simple source, but a regenerative source is required if power flow is expected from the load network. The operating principle of the proposed line conditioner is graphically shown in Fig. 2.

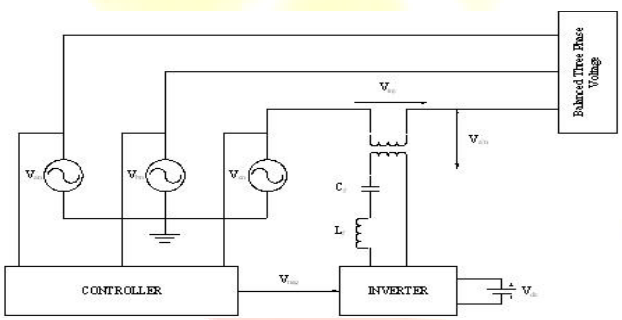

Fig. 1 Connection of the proposed Line Conditioner

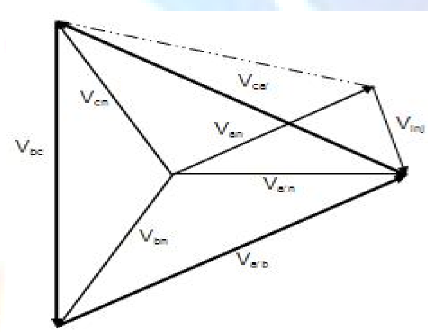

Fig. 2 Phasor diagram explaining the principle of balancing

In Fig. 2 v_{an}, v_{bn}, v_{cn} depict the input line to neutral voltages that are unbalanced. The corresponding line-to-line voltages are also unbalanced and are shown in dotted lines. The proposed active line conditioner injects a voltage vinj in phase "a". The resultant line voltages at the load terminals v_a'b, v_{bc} and v_{ca}' are balanced. The proposed system is therefore effective in nullifying the negative sequence component in the load voltage.

B. When load is sensitive:

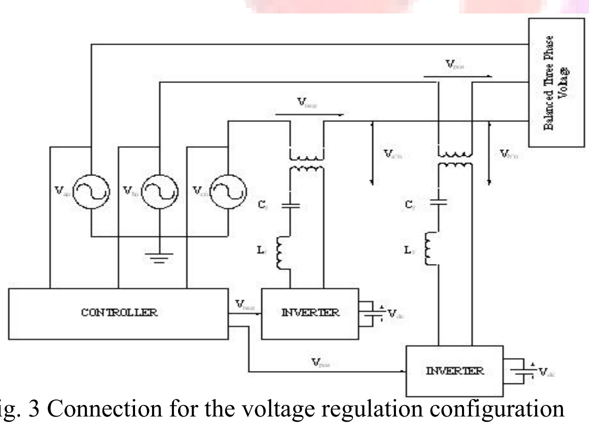

Fig. 3 Connection for the voltage regulation configuration

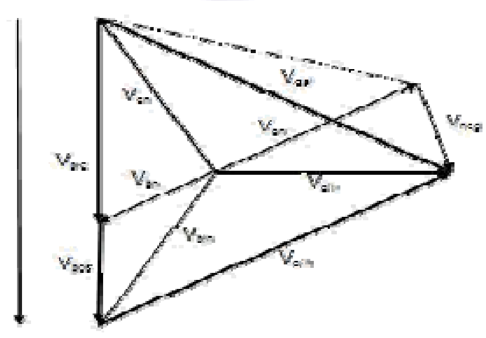

Fig. 4 Phasor diagram for combined voltage regulation and balancing.

The magnitude of the line voltage at the load terminal equals the magnitude of v_{bc}. If the load is sensitive to line voltage magnitudes the proposed method cannot ensure a rated voltage at the load terminals. For such loads, a second configuration is suggested, where instead of injecting one voltage two voltages are injected, one in phase-a and another in phase-b.

III. MODELING OF SYSTEM

In this section the expressions for the required voltage injections are derived for the balancing functions. Further the signal processing required to generate the control signal Vneg and Vpos is developed. Filtering of the inverters output can be done with the LC Series resonance connection, which is tuned for the fundamental frequency (50Hz).

A. Modelling of active line conditioner The Balancing Function:

The negative sequence voltage in a three-phase system is given by,

$Vneg = [Van + \alpha 2Vbn + \alpha Vcn]/3$ (1)

Where ($\alpha = \varepsilon j120 = -0.5 + j0.866$). If the magnitude of the injected voltage Vinj of Fig. 3 is selected equal to

$V_{inj} = - [V_{an} + \alpha^2 V_{bn} + \alpha V_{cn}]$ (2)

and this voltage is added to the phase “a” voltage. Then the resultant phase “a” voltage at the load terminals is (see Fig. 4),

$V_{aa} = V_{an} + V_{neg}$ (3)

Then inserting (2) and (3) in (1) (that is, V_{aa} for V_{an}) the negative sequence component in the load voltages is

$V_2 = \{V_{an} - [V_{an} + \alpha^2 V_{bn} + \alpha V_{cn}] + \alpha^2 V_{bn} + \alpha V_{cn}\}/3$ (4) $= 0.0$ (5)

This is the principle of the proposed Line Conditioner. The resultant positive sequence load voltage is then

$V_1 = \{V_{an} - [V_{an} + \alpha^2 V_{bn} + \alpha V_{cn}] + \alpha V_{bn} + \alpha^2 V_{cn}\}/3$ (6)

$= \{V_{bn} [\alpha - \alpha^2] + V_{cn} [\alpha^2 - \alpha]\}/$ (7)

$= \{V_{bn} - V_{cn}\}/sqrt(3)$ (8)

This is directly proportional to the input line voltage V_{bc}. Thus the positive sequence load voltage depends only on the line to line voltage V_{bc}.

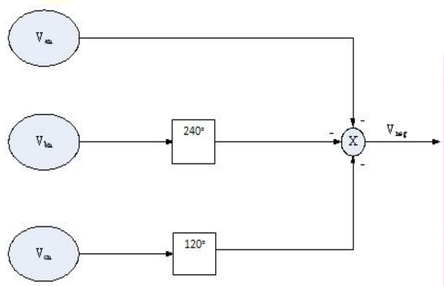

Fig. 5 Negative Sequence Signal processing to correct unbalance

To regulate the load voltage it is therefore sufficient to maintain V_{bc} at the rated value. This is the principle of the proposed voltage regulation configuration for maintaining the magnitude of the voltage across load.

The Control Circuit

To inject the required voltages a control signals V_{inj} (see Fig. 1) has to be generated. By measuring the three input voltages the required control voltage can be generated as shown in Fig. 5. The control voltage Vinj, in terms of the input phase voltages is derived below. Here, it is assumed that the load is balanced and that it is a three wire load, i.e., $V_{an} + V_{bn} + V_{cn} = 0$. The control voltage component to cancel the negative sequence line voltages can be written as, $V_{inj} = - [V_{an} + \alpha^2 V_{bn} + \alpha V_{cn}]$ (9)

The control voltage in (9) has been calculated and added to phase “a”. The unbalanced voltage then becomes balanced as shown below.

B. Design of the active line conditioner (When load is sensitive to the voltage magnitudes):

A possible modification to the proposed line conditioner to provide a rated voltage at the load terminals while providing a balanced voltage set is given in this section. The principle of this method of balancing and regulating the load voltage is explained with the help of Fig. 4 and the connection of the active line conditioner is shown in Fig. 3 and the expressions for the required voltage injections (v_{neg} and V_{pos}) are derived.

The Control Circuit

It was shown in above that the positive sequence load voltage is dependent on the input line-to- line voltage V_{bc}. To achieve the required regulating function it is necessary that V_{bc} in Fig. 4 is maintained at the rated value. Once V_{bc} is maintained at the rated value the load voltage gets regulated by the balancing function. If the magnitude of the injected voltage V_{pos} of Fig. 3 is selected equal to $V_{pos} = - V_{bn} + V_{cn} + V_{cons}$ (10)

Where V_{cons} = Constant Voltage that has to be maintained at the load terminals and having an angle of -90° with respect to the angle of V_{an}. The above control signal when added to phase "b", the changed phase voltage becomes

$$V_{b'n} = V_{bn} + V_{pos} \quad (11)$$

$$V_{b'n} = V_{bn} - V_{bn} + V_{cn} + V_{cons} \quad (12)$$

$$= V_{cn} + V_{cons} \quad (13)$$

Hence negative sequence voltage is given by

$$V_{neg} = [V_{an} + \alpha^2 V_{b'n} + \alpha V_{cn}]/3 \quad (14)$$

$$= [V_{an} + \alpha^2 \{V_{cn} + V_{cons}\} + \alpha V_{cn}]/3 \quad (15)$$

For the negative sequence voltage to be zero, the voltage is to be injected in the phase "a" and its magnitude is given by

$$V_{inj} = - [V_{an} + \alpha^2 \{V_{cn} + V_{cons}\} + \alpha V_{cn}] \quad (16)$$

Then the resultant phase "a" voltage at the load terminals is

$$V_{a'n} = V_{an} + V_{inj} \quad (17)$$

$$V_{a'n} = - \alpha^2 \{V_{cn} + V_{cons}\} - \alpha V_{cn} \quad (18)$$

$$V_2 = [V_{an} - [V_{an} + \alpha^2 \{V_{cn} + V_{cons}\} + \alpha V_{cn}] + \alpha^2 \{V_{cn} + V_{cons}\} + \alpha V_{cn}]/3 \quad (19)$$

$$= 0.0 \quad (20)$$

Hence the system is balanced.

The positive sequence component in the load voltages is

$$V_1 = [V_{a'n} + \alpha V_{b'n} + \alpha^2 V_{cn}]/3 \quad (21)$$

$$= [(\alpha - \alpha^2) V_{cons}]/3 \quad (22)$$

$$= [jV_{cons}]/\text{sqrt}(3) \quad (23)$$

From the above equation it is clear that positive sequence voltage is constant, hence the voltage across the load is maintained constant and is equal to V_{cons}. Fig. 4 shows the Phasor diagram of the system, which indicates the injection of V_{neg} as well as V_{pos} to balance the system in respect of balancing and the magnitude; hence this system shall be used when load is sensitive to the voltage magnitude

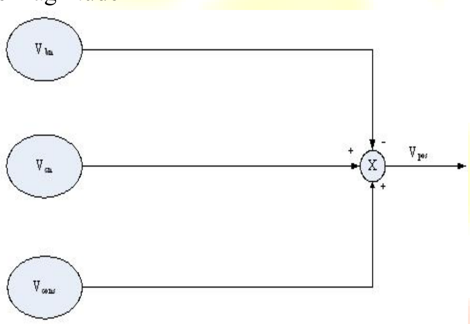

Fig. 6 Positive Sequence Signal Processing to correct unbalance

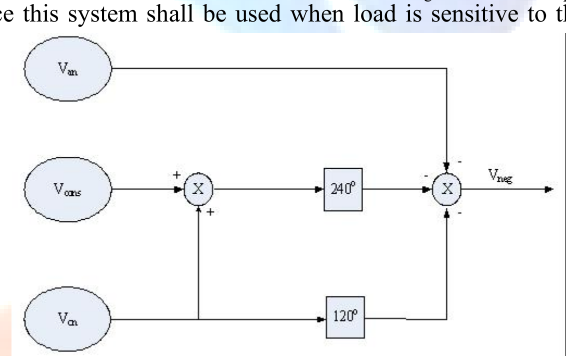

Fig.7 Negative Sequence Signal Processing to correct unbalance

Fig. 6 and 7 shows the block diagram used to generate the positive sequence signal and negative sequence signal respectively.

IV. Simulated Performance of Line Conditioner

A. When load is normal

To take into consideration a wide range of possible unbalance conditions, the input phase voltages Van, Vbn and Vcn are changed in magnitude between 200 V and 260 V maintaining their phase angles constant at $\varphi_a = 0^o$, $\varphi_b = 240^o$ and $\varphi_c = 120^o$ and then by changing the phase angle maintaining their magnitude constant at their rated value. From the simulations the following quantities are observed:

1. Unbalanced Source-end positive sequence voltage
2. Load-end positive sequence voltages.
3. Magnitude of the required injected voltages.
4. The phase angle of the resulting line-to-line voltage V_{ab} with respect to V_a.

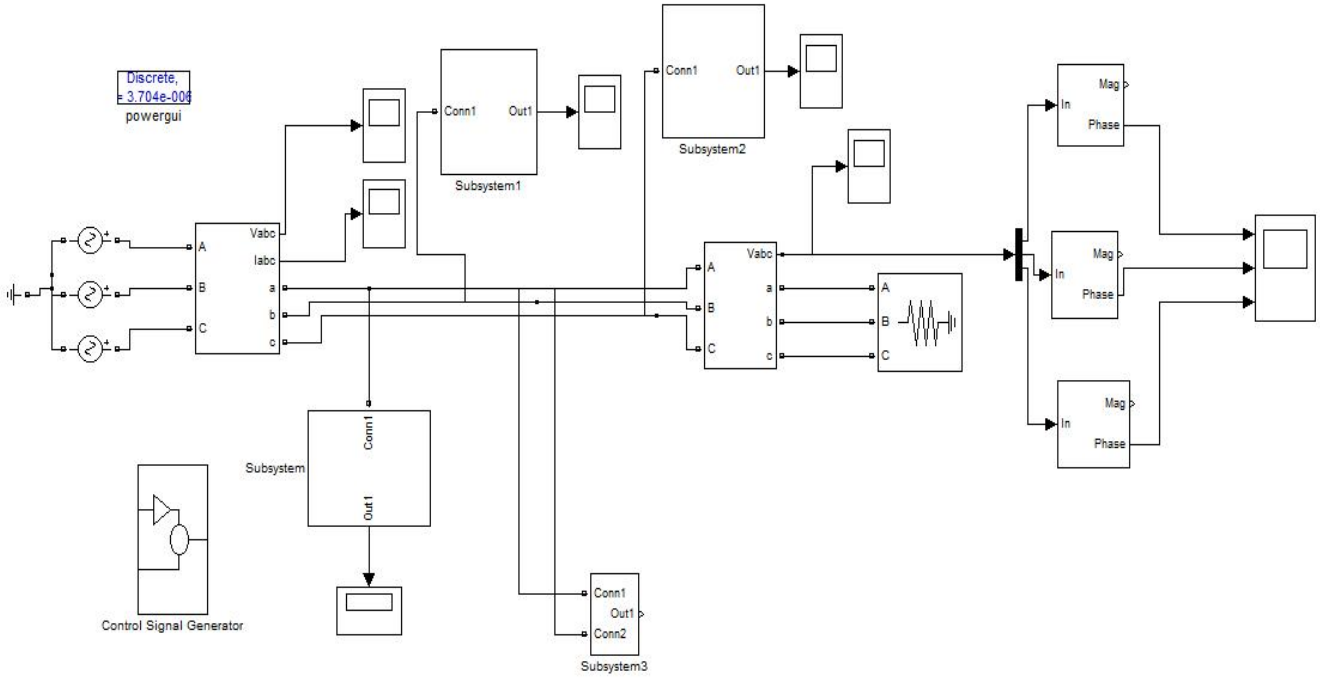

Fig. 8 Matlab/Simulink block diagram of the system with the control technique (when load is not sensitive)

Fig. 9, 10 and 11 shows the unbalanced line to neutral input voltage and the balanced line to line voltages $V_{a\square b}$, V_{bc} and $V_{ca\square}$ respectively.

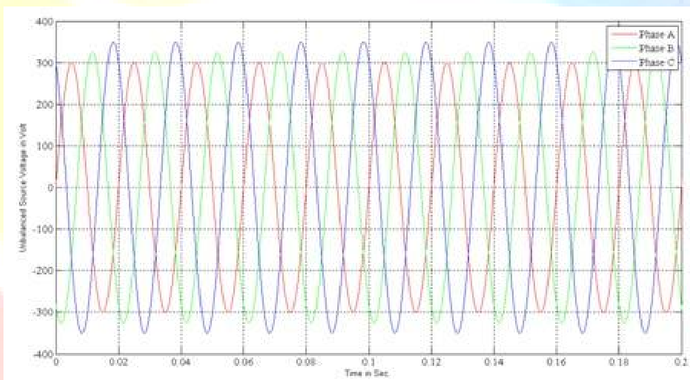

Fig. 9 Unbalanced input line to neutral Voltage

Fig. 9, 10 and 11 shows the angle of the line voltages at the load end, which clearly indicates that the load line voltages are balanced and 30o ahead of their respective phase voltages. Hence, to get the rated voltage magnitude across the load terminal, positive sequence voltage signal need to be generated along with negative sequence voltage signal, the calculation behind the generation of negative and positive sequence signal has already explained.

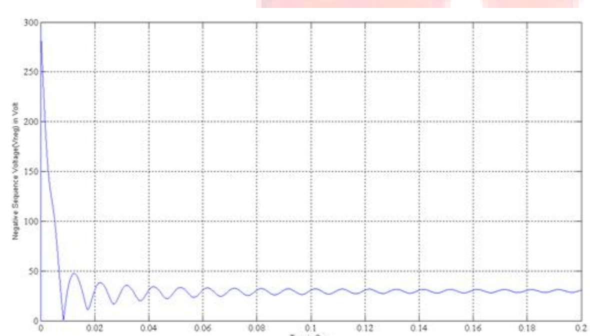

Fig. 10 Injected Negative Sequence Voltage V_{neg}

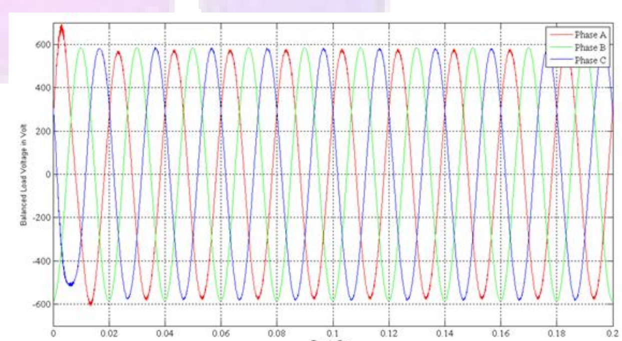

Fig. 11 Balanced line to line voltages $v_{a\square b}$, v_{bc} and v_{ca}

B. When load is sensitive load

In sensitive load we are using a particular unbalanced input line to neutral voltage, injected negative sequence voltage V_{neg}, injected positive sequence voltage V_{pos} and we get balanced line to line voltages $V_{a\square b\square}$, $V_{b\square c}$ and $V_{ca\square}$. For this load has been in progress as my project work.

V. CONCLUSION

The issue of unbalancing, which normally occurs in the transmission line because of unbalanced loading, switching and lightning surges. The unbalancing in the line causes overheating of the equipment connected to that line, which reduces the life of equipment used. Hence balancing of the load voltage becomes necessary, which is being compensated at each moment by the compensator connected in series with the transmission line, which injects the voltage in the transmission line by the value which system requires. The injection of voltage can be in any one phase and two phases.

The advantage of injecting voltage in two phases over injecting in any one phase is that we get the desired voltage profile, which is at rated value in terms of phase difference as well as in terms of voltage magnitude but at the same time it has the disadvantages of cost. Since method 2 consists of two voltage source inverter along with the required accessories, this method is quite costly. If the system is not sensitive to the voltage variation, the method 1, which is the injection of voltage in any phases can be adopted, which is cheaper than the method 2. Hence, there must be trade-off between the economic requirement and quality requirement. A design Procedure for the proposed approaches has been shown. Finally, results on a MATLAB/SIMULINK verifying the principle are provided.

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