C.GOPI, M.KISHOR/ International Journal of Engineering Research and Applications (IJERA)
ISSN: 2248-9622 www.ijera.com
Vol. 2, Issue 3, May-Jun 2012, pp.1042-1047

Power Upgrading of Transmission Line by Injecting DC Power in to AC Line with the help of ZIG-ZAG Transformer

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ABSTRACT
We never loaded a long extra high voltage to their thermal limits in order to keep sufficient margin against transient instability. With this scheme proposed in this paper, it is possible to load these lines very near to their thermal limits. Here we inject dc power in to dc transmission line to carry usual ac along with dc superimposed on it. The added power flow does not cause any transient instability.

This paper presents the feasibility of converting a double circuit ac line into composite ac–dc power transmission line to get the advantages of parallel ac–dc transmission to improve stability and damping out oscillations. Simulation is carried out for the coordinated control as well as independent control of ac and dc power transmissions. No alterations of conductors, insulator strings, and towers of the original line are needed. Substantial gain in the loadability of the line is obtained. Master current controller senses ac current and regulates the dc current orders for converters online such that conductor current never exceeds its thermal limit.

Index Terms—**Extra high voltage transmission, flexible ac transmission system, power system computer-aided design simulation, simultaneous ac–dc power transmission.**

I. INTRODUCTION
The feasibility study of conversion of a double circuit ac line to composite ac–dc line without altering the original line conductors, tower structures, and insulator strings has been presented. In this scheme, the dc power flow is point-to- point bipolar transmission system. Clerici et al. [7] suggested the conversion of ac line to dc line for substantial power upgrading of existing ac line. However, this would require major changes in the tower structure as well as replacement of ac insulator strings with high creepage dc insulators.

The novelty of our proposed scheme is that the power transfer enhancement is achieved without any alteration in the existing EHV ac line. The main object is to gain the advantage of parallel ac–dc transmission and to load the line close to its thermal limit. In recent years, environmental, right-of-way, and cost concerns have delayed the construction of a new transmission line, while demand of electric power has shown steady but geographically uneven growth. The power is often available at locations not close to the growing load centers but at remote locations. These locations are largely determined by regulatory policies, environmental acceptability, and the cost of available energy. The wheeling of this available energy through existing long ac lines to load centers has a certain upper limit due to stability considerations. Thus, these lines are not loaded to their thermal limit to keep sufficient margin against transient instability.

The authors of this paper have earlier shown that extra high voltage (EHV) ac line may be loaded to a very high level by using it for simultaneous ac–dc power transmission as reported in references [5] and [6]. The basic proof justifying the simultaneous ac–dc power transmission is explained in reference [6]. In the above references, simultaneous ac–dc power transmission was first proposed through a single circuit ac transmission line. In these proposals Mono-polar dc transmission with ground as return path was used. There were certain limitations due to use of ground as return path. Moreover, the instantaneous value of each conductor voltage with respect to ground becomes higher by the amount of the dc voltage, and more discs are to be added in each insulator string to withstand this increased voltage. However, there was no change in the conductor separation distance, as the line-to-line voltage remains unchanged.

The flexible ac transmission system (FACTS) concepts, based on applying state-of-the-art power electronic technology to existing ac transmission system, improve stability to achieve power transmission close to its thermal limit [1]–[4]. Another way to achieve the same goal is simultaneous ac–dc power transmission in which the conductors are allowed to carry superimposed dc current along with ac current.

II. SIMULTANEOUS AC–DC POWER TRANSMISSION

Fig. 1 depicts the basic scheme for simultaneous ac–dc power flow through a double circuit ac transmission line. The dc power is obtained through line commutated 12-pulse Rectifier Bridge used in conventional HVDC and injected to the neutral point of the zigzag connected secondary of sending end transformer and is reconverted to ac again by the conventional line commutated 12-pulse bridge inverter at the receiving end. The inverter bridge is again connected to the neutral of zig-zag connected winding of the receiving end transformer. The double circuit ac transmission line carriers both three-phase ac and dc power. Each conductor of each line carries one third of the total dc current along with ac current I_a. Resistance being equal in all the three phases of secondary winding of zig-zag transformer as well as the three conductors of the line, the dc current is equally divided among all the three phases. The three conductors of the second line provide return path for the dc current. Zig-zag connected winding is used at both ends to avoid saturation of transformer due to dc current.

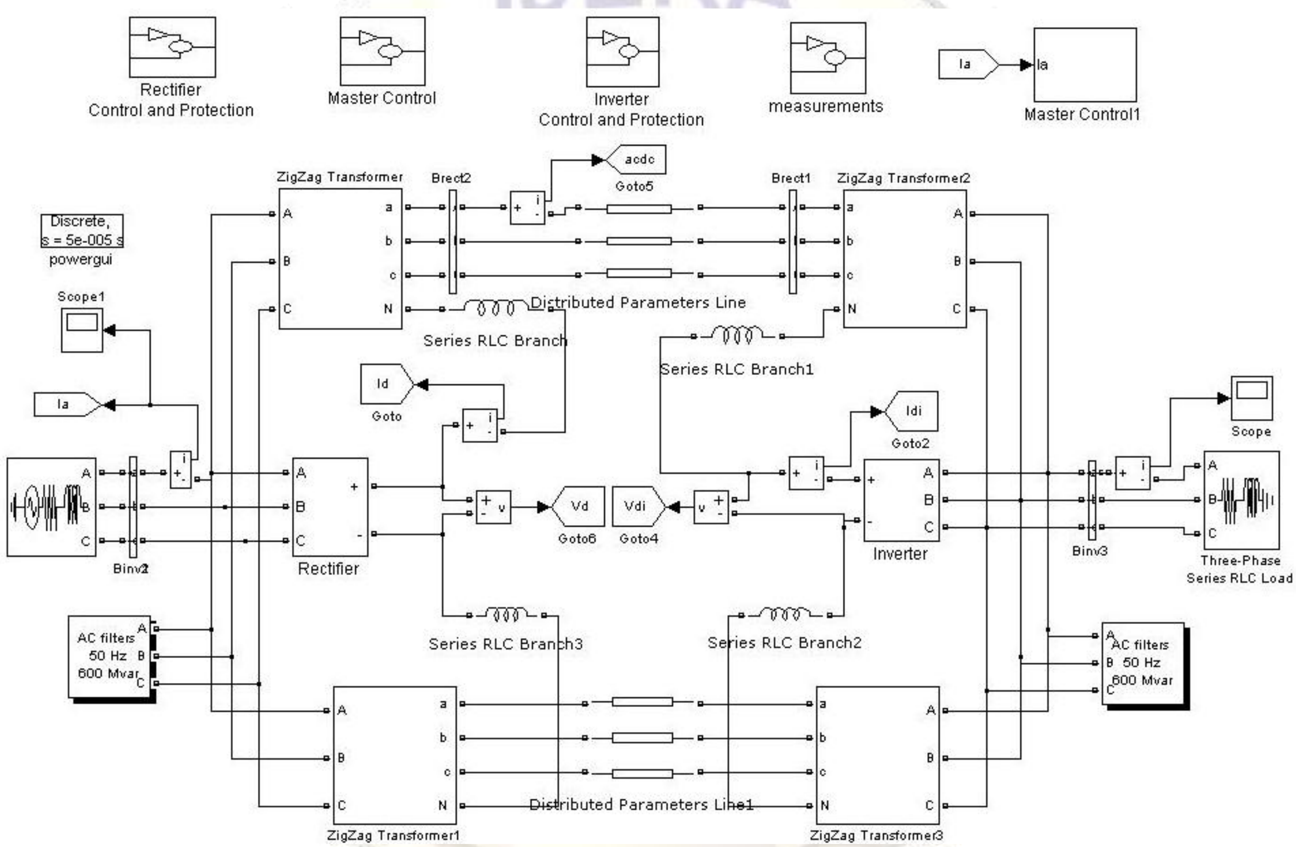

Fig. 1. Simulation diagram for composite ac-dc transmission.

Two fluxes produced by the dc current ($I_d/3$) flowing through each of a winding in each limb of the core of a zig-zag transformer are equal in magnitude and opposite in direction. So the net dc flux at any instant of time becomes zero in each limb of the core. Thus, the dc saturation of the core is avoided. A high value of reactor X_d is used to reduce harmonics in dc current.

In the absence of zero sequence and third harmonics or its multiple harmonic voltages, under normal operating conditions, the ac current flow through each transmission line will be restricted between the zigzag connected windings and the three conductors of the transmission line. Even the presence of these components of voltages may only be able to produce negligible current through the ground due to high value of X_d. Assuming the usual constant current control of rectifier and constant extinction angle control of inverter [4], [8]–[10], the equivalent circuit of the scheme under normal steady-state operating condition is given in Fig. 2. The dotted lines in the figure show the path of ac return current only. The second transmission line carries the return dc current I_d, and each conductor of the line carries $I_d/3$ along with the ac current per phase. V_{dro} and V_{dio} are the maximum values of rectifier and inverter side dc voltages and are equal to $(3\sqrt{2}/\pi)$ times converter ac input line-to-line voltage. R, L, and C are the line parameters per phase of each line. R_{cr}, R_{ci} are commutating resistances, and α, γ are firing and extinction angles of rectifier and inverter, respectively. Neglecting the resistive drops in the line conductors and transformer windings due to dc current, expressions for ac voltage and current, and for active and reactive powers in terms of A, B, C, and D parameters of each line may be written as

$$E_s = AE_R + BI_R \quad (1)$$

$$I_S = CE_R + DI_R \quad (2)$$

$$P_S + jQ_S = -E_S E^*_R/B^* + D^* E^2_S/B^* \quad (3)$$

$$P_R + jQ_R = E_S E^*_R/B^* - A^* E^2_R/B^* \quad (4)$$

Neglecting ac resistive drop in the line and transformer, the dc power P_{dr} and P_{di} of each rectifier and inverter may be expressed as

$$P_{dr} = V_{dr} I_d \quad (5)$$

$$P_{di} = V_{di} I_d \quad (6)$$

Reactive powers required by the converters are

$$Q_{dr} = P_{dr} \tan\theta_r \quad (7)$$

$$Q_{dI} = P_{dI} \tan\theta_I \quad (8)$$

$$\cos\theta_r = [\cos\alpha + \cos(\alpha + \mu_R)]/2 \quad (9)$$

$$\cos\theta_r = [\cos\gamma + \cos(\gamma + \mu_i)]/2 \quad (10)$$

μ_i and μ_r are commutation angles of inverter and rectifier, respectively, and total active and reactive powers at the two ends are

$$P_{st} = P_s + P_{dr} \text{ and } P_{rt} = P_R + P_{di} \quad (11)$$

$$Q_{st} = Q_s + Q_{dr} \text{ and } Q_{rt} = Q_R + Q_{di} \quad (12)$$

Transmission loss for each line is

$$P_L = (P_S + P_{dr}) - (P_R + P_{di}) \quad (13)$$

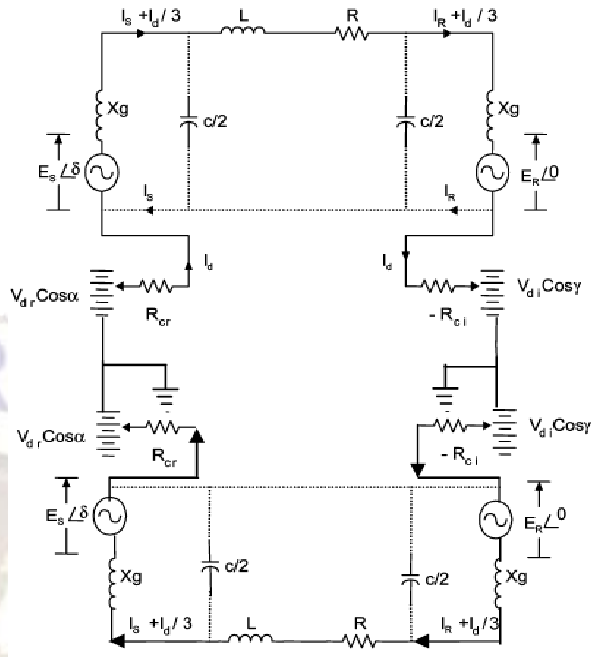

Fig. 2. Equivalent circuit.

I_a being the rms ac current per conductor at any point of the line, the total rms current per conductor becomes

$$I = [I^2_a + (I_d/3)^2]^{1/2}$$

Power loss for each line = $P_L \approx$ 3I2R

The net current I in any conductor is offseted from zero. In case of a fault in the transmission system, gate signals to all the SCRs are blocked and that to the bypass SCRs are released to protect rectifier and inverter bridges. The current in any conductor is no more offseted. Circuit breakers (CBs) are then tripped at both ends to isolate the faulty line. CBs connected at the two ends of transmission line interrupt current at natural current zeroes, and no special dc CB is required. Now, allowing the net current through the conductor equal to its thermal limit (I_{th}).

$$I_{th} = [I^2_a + (I_d/3)^2]^{1/2} \quad (14)$$

Let V_{ph} be per-phase rms voltage of original ac line. Let also V_a be the per-phase voltage of ac component of composite ac–dc line with dc voltage V_d superimposed on it. As insulators remain unchanged, the peak voltage in both cases should be equal

$$V_{max} = \sqrt{2}V_{ph} = V_d + \sqrt{2}V_a \quad (15)$$

ISSN: 2248-9622 www.ijera.com
Vol. 2, Issue 3, May-Jun 2012, pp.1042-1047

Electric field produced by any conductor possesses a dc component superimpose on it a sinusoidally varying ac component. However, the instantaneous electric field polarity changes its sign twice in a cycle if $(V_d/V_a) < \sqrt{2}$ is insured. Therefore, higher creepage distance requirement for insulator discs used for HVDC lines are not required. Each conductor is to be insulated for V_{max}, but the line-to-line voltage has no dc component and $V_{LLmax}=\sqrt{6}V_a$. Therefore, conductor-to-conductor separation distance of each line is determined only by rated ac voltage of the line. Allowing maximum permissible voltage offset such that the composite voltage wave just touches zero in each every cycle;

$$V_d = V_{ph}/\sqrt{2} \text{ and } V_a = V_{ph}/2 \tag{16}$$

The total power transfer through the double circuit line before conversion is as follows:

$$P'_{total} \approx 3V_{ph}{}^2 \sin\delta_1/X \tag{17}$$

Where X is the transfer reactance per phase of the double circuit line, and δ_1 is the power angle between the voltages at the two ends.

To keep sufficient stability margin, δ_1 is generally kept low for long lines and seldom exceeds 30^0. With the increasing length of line, the loadability of the line is decreased [4]. An approximate value of δ_1 may be computed from the loadability curve by knowing the values of surge impedance loading (SIL) and transfer reactance of the line

$$P'_{total} = 2.M.SIL \tag{18}$$

Where M is the multiplying factor and its magnitude decreases with the length of line. The value of M can be obtained from the loadability curve [4].

The total power transfer through the composite line

$$P_{total} = P_{ac} + P_{dc} = 3V_a{}^2 \sin\delta_2/X + 2V_d I_d \tag{19}$$

The power angle between the ac voltages at the two ends of the composite line may be increased to a high value due to fast controllability of dc component of power. For a constant value of total power, may be modulated by fast control of the current controller of dc power converters. Approximate value of ac current per phase per circuit of the double circuit line may be computed as

$$I_a = V(\sin\delta/2)/X \tag{20}$$

The rectifier dc current order is adjusted online as

$$I_d = \sqrt[3]{I_{t\square}^{*2} - I_a^{*2}} \tag{21}$$

In case of a fault in the transmission system, gate signals to all the SCRs are blocked and that to the bypass SCRs are released to protect rectifier and inverter bridges. A surge diverter connected between the zig-zag neutral and the ground protects the converter bridge against any over voltage.

III. DESCRIPTION OF THE SYSTEM MODEL

The network depicted in Fig. 1 was studied using MATLAB. A synchronous machine is feeding power to infinite bus via a double circuit, three-phase, 400-KV, 50-Hz, 450-Km ac transmission line. The 2750-MVA (5 550), 24.0-KV synchronous machine is dynamically modeled, a field coil on d-axis and a damper coil on q-axis, by Park's equations with the frame of reference based in rotor [4].

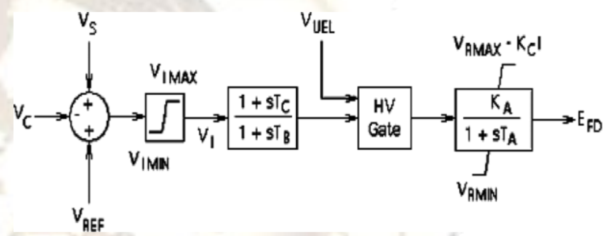

Fig. 3. IEEE type AC4A excitation system.

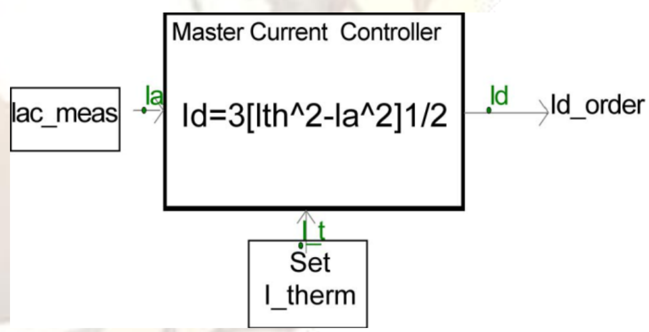

Fig. 4. Master current controller.

Transmission lines are represented as the Bergeron model. It is based on a distributed LC parameter travelling wave line model, with lumped resistance. It represents the L and C elements of a PI section in a distributed manner (i.e., it does not use lumped parameters). It is roughly equivalent to using an infinite number of PI sections, except that the resistance is lumped (1/2 in the middle of the line, 1/4 at each end). Like PI sections, the Bergeron model accurately represents the fundamental frequency only. It also represents impedances at other frequencies, except that the losses do not change. This model is suitable for studies

ISSN: 2248-9622 www.ijera.com
Vol. 2, Issue 3, May-Jun 2012, pp.1042-1047

where the fundamental frequency load flow is most important.

The converters on each end of dc link are modeled as line commutated two six- pulse bridge (12-pulse), Their control system consist of constant current (CC) and constant extinction angle (CEA) and voltage dependent current order limiters control. The converters are connected to ac buses via Y-Y and Y- converter transformers.

Each bridge is a compact power system computer-aided design representation of a dc converter, which includes a built in six-pulse Graetz converter bridge (can be inverter or rectifier), an internal phase locked oscillator (PLO), firing and valve blocking controls, and firing angle (α)/extinction angle (γ) measurements. It also includes built in RC snubber circuits for each thyristor. The controls used in dc system are those of CIGRE Benchmark [14], modified to suit at desired dc voltage. Ac filters at each end on ac sides of converter transformers are connected to filter out 11th and 13th harmonics.

These filters and shunt capacitor supply reactive power requirements of converters. It is roughly equivalent to using an infinite number of PI sections, except that the resistance is lumped (1/2 in the middle of the line, 1/4 at each end). Like PI sections, the Bergeron model accurately represents the fundamental frequency only.

IV. SIMULATION RESULTS

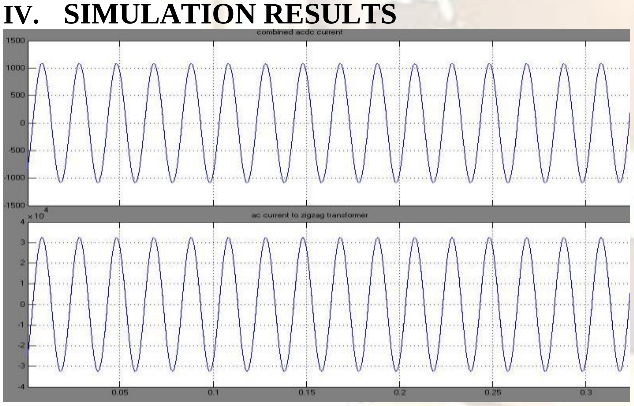

Fig. 5. Combined ACDC Current and AC current to Zig-zag Transformer.

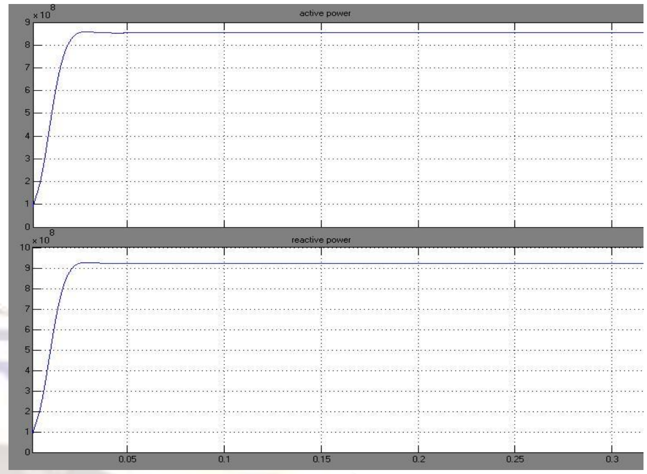

Fig. 6. Active and Reactive Powers.

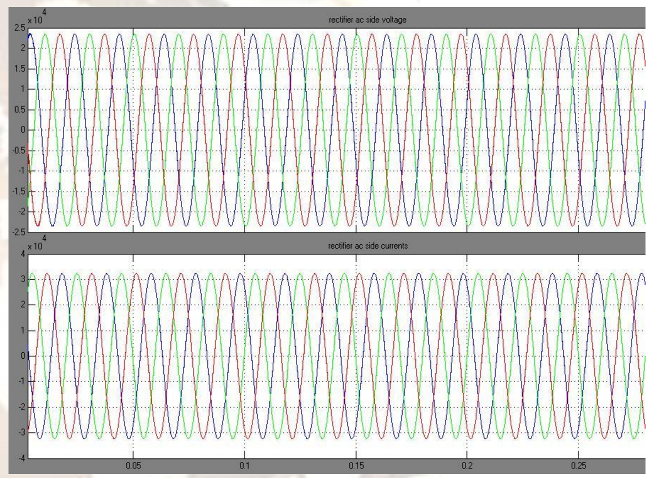

Fig. 7. Rectifier AC side Voltage and Current.

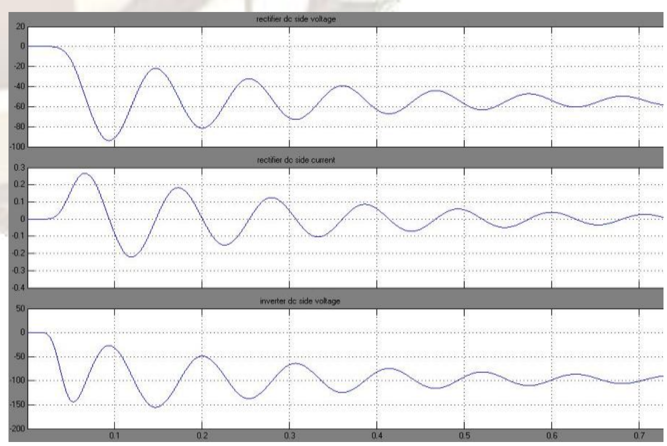

Fig. 8. Rectifier DC voltage and Current Inverter DC side Voltage.

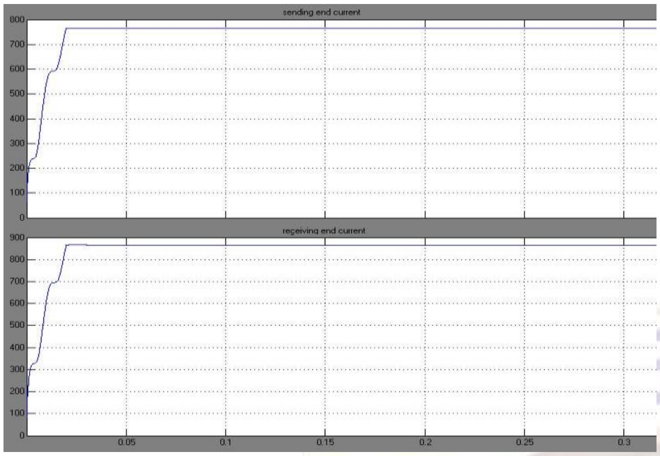

Fig. 9. Sending and Receiving end currents.

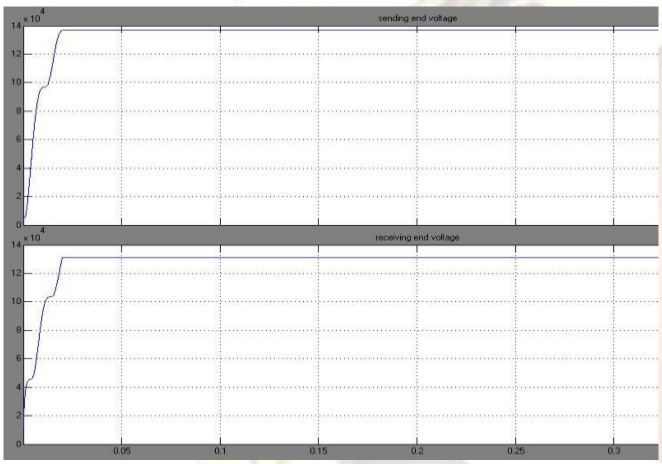

Fig. 10. Sending and receiving end voltages.

V. CONCLUSION

The feasibility to convert ac transmission line to a composite ac–dc line has been demonstrated. For the particular system studied, there is substantial increase (about 83.45%) in the loadabilty of the line. The line is loaded to its thermal limit with the superimposed dc current. The dc power flow does not impose any stability problem. The advantage of parallel ac–dc transmission is obtained. Dc current regulator may modulate ac power flow. There is no need for any modification in the size of conductors, insulator strings, and towers structure of the original line. The optimum values of ac and dc voltage components of the converted composite line are 1/2 and times the ac voltage before conversion, respectively.

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