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Stability Enhancement of Power System by Controlling Hvdc Power Flow through the Same Ac Transmission Line

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ABSTRACT
Long extra high voltage (EHV) ac lines cannot be loaded to their thermal limits in order to keep sufficient margin against transient instability. With the scheme proposed in this paper, it is possible to load these lines very close to their thermal limits. The conductors are allowed to carry usual ac along with dc superimposed on it. The added dc 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 and experimental studies are 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.
The present paper is implemented by using MATLAB/SIMULINK.
Key word: Extra high voltage (EHV) transmission, flexible ac transmission system (FACTS), simultaneous ac–dc power transmission.

I. INTRODUCTION

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 present situation demands the review of traditional power transmission theory and practice, on the basis of new concepts that allow full utilization of existing transmission facilities without decreasing system availability and security. 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. 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. Ac and dc power flow independently, and the added dc power flow does not cause any 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. The basic proof justifying the simultaneous ac–dc power transmission is explained in reference. 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. In this paper, 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. 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.

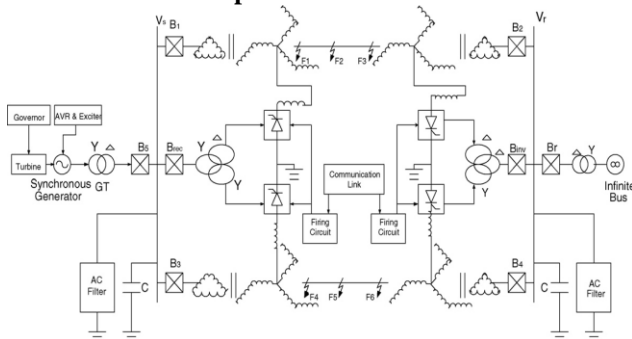## II. SIMULTANEOUS AC – DC POWER TRANSMISSION

2.1 Basic concept

Fig 2.1: Basic Scheme for composite AC-DC transmission

Fig 2.1 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. 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. Two fluxes produced by the DC current (Id/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 zig-zag 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, the equivalent circuit of the scheme under normal steady-state operating condition is given in Fig. 2.2.
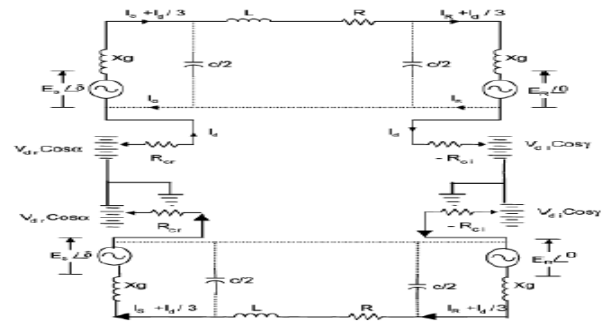

Fig. 2.2   Equivalent circuit

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

$$E_s = AE_R + BI_R \qquad (2.1)$$
$$I_S = CE_R + DI_R \qquad (2.2)$$
$$P_S + JQ_S = -E_S E^*_R/B^* + D^*E^2_R/B^* \qquad (2.3)$$
$$P_R + JQ_R = -E^*_S E_R/B^* - A^*E^2_R/B^* \qquad (2.4)$$

Neglecting AC resistive drop in the line and transformer, the DC power Pdr and Pdi of each rectifier and inverter may be expressed as

$$P_{dr} = V_{dr} I_d \qquad (2.5)$$
$$P_{di} = V_{di} I_d \qquad (2.6)$$

Reactive powers required by the converters are

$$Q_{dr} = P_{dr} \tan\theta_r \qquad (2.7)$$
$$Q_{di} = P_{di} \tan\theta_I \qquad (2.8)$$
$$\cos\theta_r = (\cos\alpha + \cos(\alpha + \mu_r))/2 \qquad (2.9)$$
$$\cos\theta_i = (\cos\alpha + \cos(\alpha + \mu_i))/2 \qquad (2.10)$$

μr and μi are commutation angles of inverter and rectifier, respectively, and total active and reactive powers at the two ends areTransmission loss for each line is

$$P_L = (P_S + P_{dr}) - (P_R + P_{di}) \qquad (2.11)$$

Ia being the rms AC current per conductor at any point of the line, the total rms current per conductor becomes

$$I= [I_a^2+(I_d/3)^2]^{1/2} \tag{2.12}$$

Power loss for each line $P_L \approx 3I^2R$ (2.13)

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}).

$$I=[I_a^2+(I_d/3)^2]^{1/2} \tag{2.14}$$

Let Vph be per-phase rms voltage of original ac line. Let Vph also Va be the per-phase voltage of ac component of composite AC-DC line with dc Vd voltage superimposed on it. As insulators remain unchanged, the peak voltage in both cases should be equal

$$V_{max} = \sqrt{2}V_{ph} = V_d+\sqrt{2}V_a \tag{2.15}$$

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 creep age 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 VLL max $=\sqrt{6}V_a$. 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;

$$V_d= V_{ph}/\sqrt{2} \text{ and } V_a = V_{ph}/2 \tag{2.16}$$

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

$$P'_{total} \approx 3 V_{ph}^2 \sin \delta_1/X \tag{2.17}$$

Where X is the transfer reactance per phase of the double circuit line, δ_1 and 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 30o. With the increasing length of line, the load ability of the line is decreased. An approximate value of δ_1 may be computed from the load ability curve by knowing the values of surge impedance loading (SIL) and transfer reactance X of the line.

$$P'_{total} = 2.M.SIL \tag{2.18}$$

Where M is the multiplying factor and its magnitude decreases with the length of line. The value of M can be obtained from the load ability curve.
The total power was transfer through the composite line.

$$P_{total} = P_{ac} + P_{dc} = 3V_a^2 \sin\delta_2/X+2V_dI_d \tag{2.19}$$

The power angle δ_2 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, Pac 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

$$I_a= V(\sin\delta/2)/X \tag{2.20}$$

The rectifier DC current order is adjusted online as

$$I_d=3\sqrt{I_{th}^{*2}-I_a^{*2}} \tag{2.21}$$

Preliminary qualitative analysis suggests that commonly used techniques in HVDC/AC system may be adopted for the purpose of the design of protective scheme, filter, and instrumentation network to be used with the composite line for simultaneous AC-DC power flow. 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. CBs are then tripped at both ends to isolate the complete system. A surge diverter connected between the zig-zag neutral and the ground protects the converter bridge against any over voltage.

2.2 Economic consideration

To get the advantages of parallel AC–DC transmission in order to improve stability and damping oscillations, the conversion of a double circuit AC line for simultaneous AC–DC power flow has been considered such that no alterations of conductor, insulator string and tower structure of the original line are required. The optimum values of AC phase and DC voltages of the converted line are 1/2 and 1/√2 times the phase voltage before conversion, respectively. The cost of transmission line includes the investment and operational costs. The investment includes costs of Right of Way (RoW), transmission tower, conductors, insulators, labour and terminal equipments. The operational costs include mainly the cost of losses. Additional costs of compensation and its terminal equipments also influences the AC line cost. DC transmission does not require compensation but the terminal equipment costs are increased due to the presence of converters and filters. Replacement of Y-connected transformer in simultaneous AC–DC

power transmission with zig-zag transformer is not likely to increase the cost, because it transfers only 25% of total power by transformer action. Also, the AC voltage reduces to 50% of the original AC voltage. However, the neutral point of this transformer needs insulation to withstand DC voltage. The load ability is observed to get doubled

or even more with the simultaneous AC–DC power flow for a line with length of 500 km or longer. When an existing AC line is converted to simultaneous AC–DC line, instead of adding separate parallel DC, the additional investment on new DC line and on AC line compensations are saved.

III. MODELLING OF COMPOSITE AC-DC SYSTEM
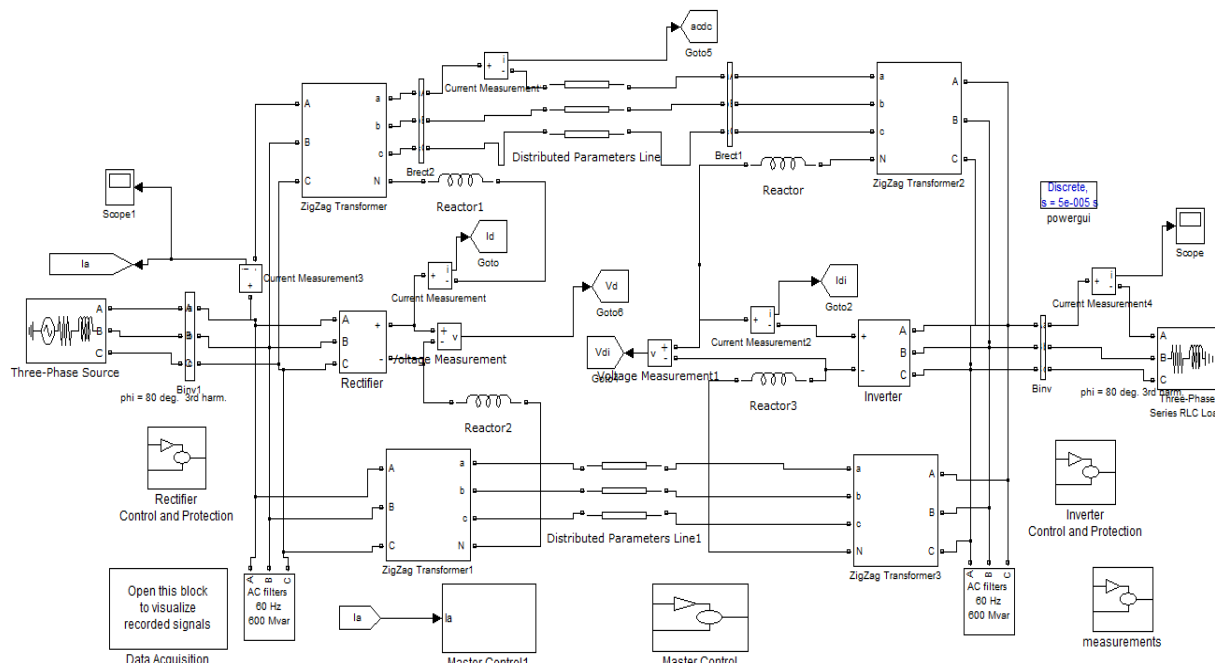
Fig 3: Simulink Model of Simultaneous AC-DC Transmission

IV. PROPOSED APPLICATIONS

1. Long EHV ac lines can not be loaded to their thermal limit to keep sufficient margin against transient instability and to keep voltage regulation within allowable limit, the simultaneous power flow does not imposed any extra burden on stability of the system, rather it improves the stability. The resistive drop due to dc current being very small in comparison to impedance drop due to ac current, there is also no appreciable change in voltage regulation due to superimposed dc current.

2. Therefore one possible application of simultaneous ac-dc transmission is to load the line close to its thermal limit by transmitting additional dc power. Figure3 shows the variation of Pt/Pac for changing values of k and x at unity power factor. However, it is to be noted that additional conductor insulation is to be provided due to insertion of dc.

3. Necessity of additional dc power transmission will be experienced maximum during peak load period which is characterized with lower than rate voltage. If dc power is injected during the

peak loading period only with V d being in the range of 5% to 10% of E ph, the same transmission line without having any enhanced insulation level may be allowed to be used For 10.2% more power may be transmitted.

4. By adding a few more discs in insulator strings of each phase conductor with appropriate modifications in cross-arms of towers insulation level between phase to ground may be increased to a high value, which permits proportional increase in Emax, Therefore higher value of Vd may be used to increase dc and total power flow through the line. This modification in the exiting ac lines is justified due to high cost of a separate HVDC line.

5. With the very fast electronic control of firing angle (α) and extinction angle (γ) of the converters, the fast control of dc power may also be used to improve dynamic stability and damping out oscillations in the system similar to that of the ac-dc parallel transmission lines.

6. Control of α and γ also controls the rectifier and inverter VAR requirement and therefore, may be used to control the voltage profile of the

transmission line during low load condition and works as inductive shunt compensation. It may also be considered that the capacitive VAR of the transmission line is supplying the whole or part of the inductive VAR requirement of the converter system. In pure HVDC system capacitance of transmission line cannot be utilized to compensate inductive VAR.

7. The independent and fast control of active and reactive power associated with dc, superimposed with the normal ac active and reactive power may be considered to be working as another component of FACTS.

8. Simultaneous ac-dc power transmission may find its application in some special cases of LV and MV distribution system. When 3-phase power in addition to dc power is supplied to a location very near to a furnace or to a work place having very high ambient temperature, rectification of 3-phase supply is not possible at that location using semiconductor rectifier. In such place simultaneous ac-dc transmission is advantageous. In air craft 3-phase loads are generally fed with higher frequency supply of about 400Hz and separate line is used for dc loads. Skin effect restricts the optimum use of distribution wires at high frequency. Simultaneous ac-dc power transmission reduces both volume and weight of distributors.
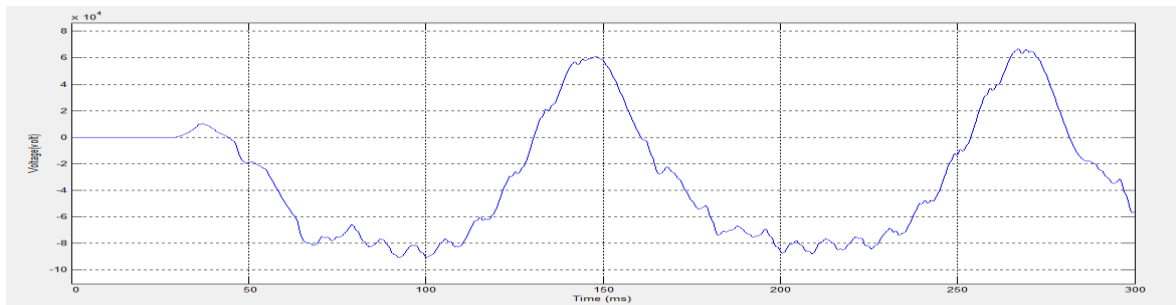
9. Another possible application is the transmission of dc power generated by PV solar cells directly to remote dc loads through 3-phase ac line. In all cases of separate dc supply filter networks are not required.
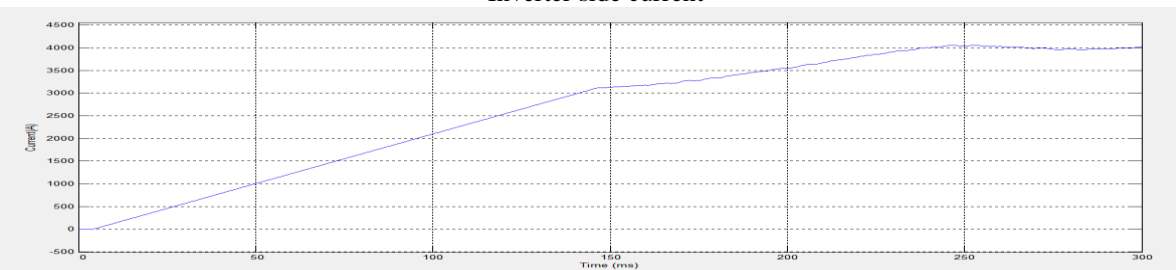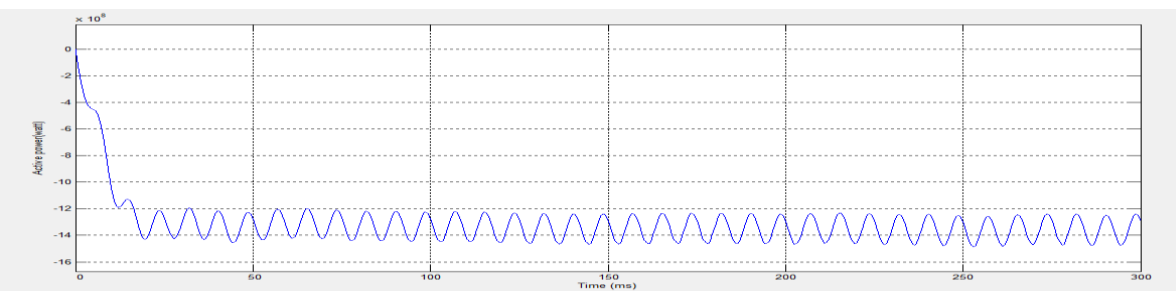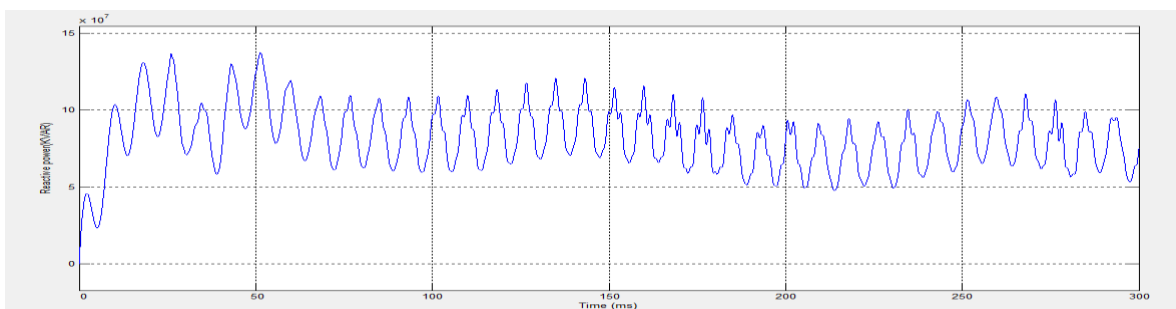
V. SIMULATED RESULTS
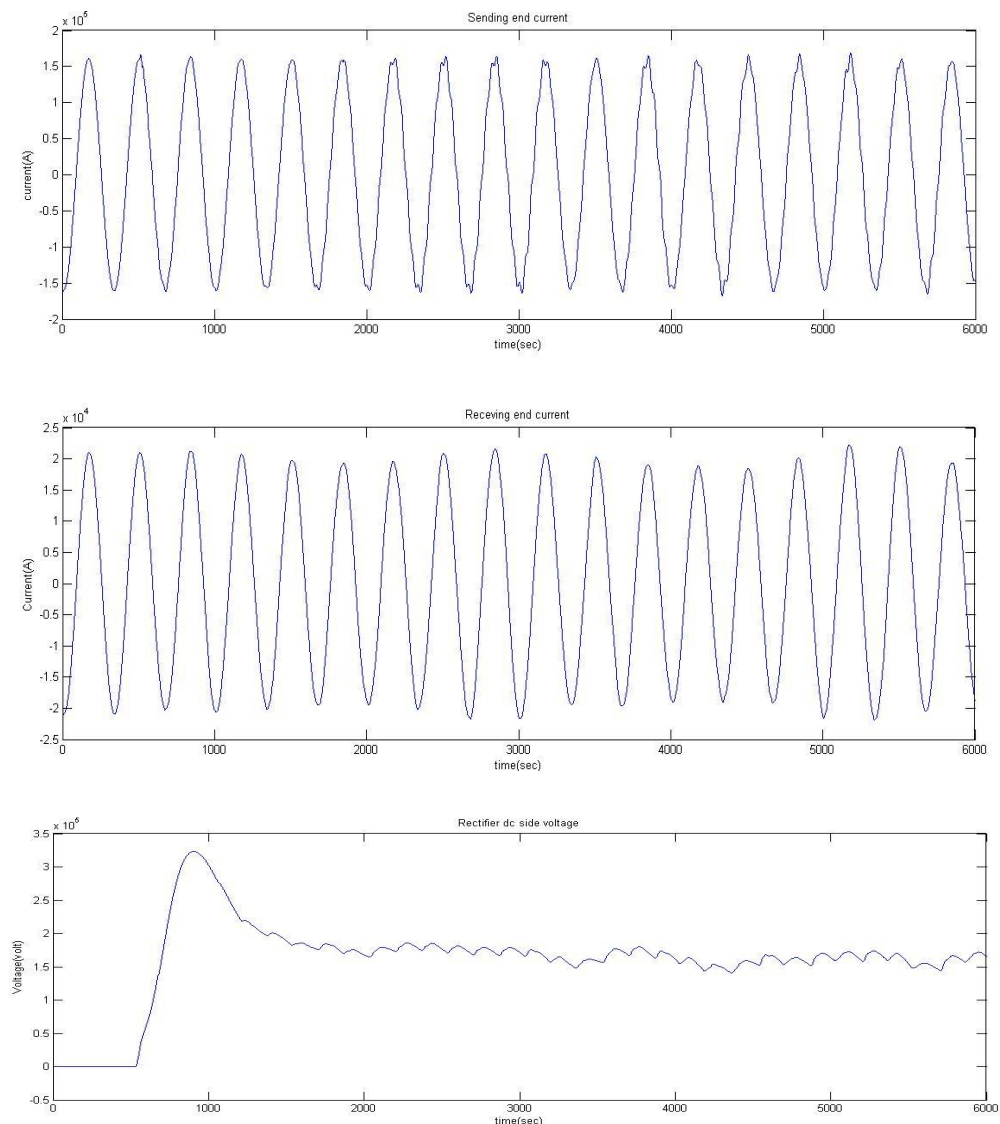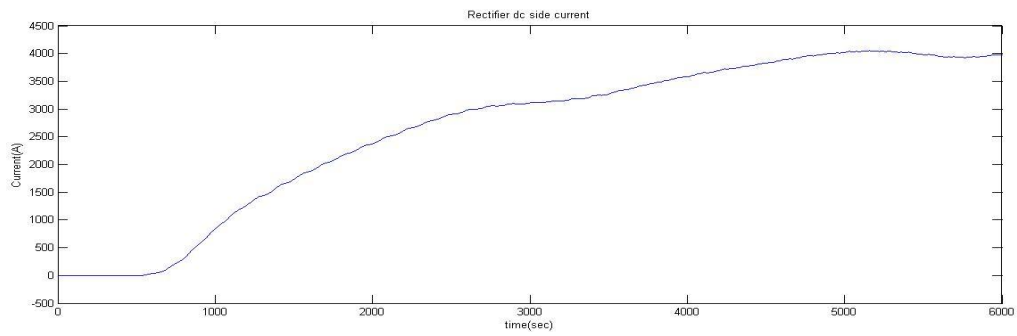
Inverter side voltage

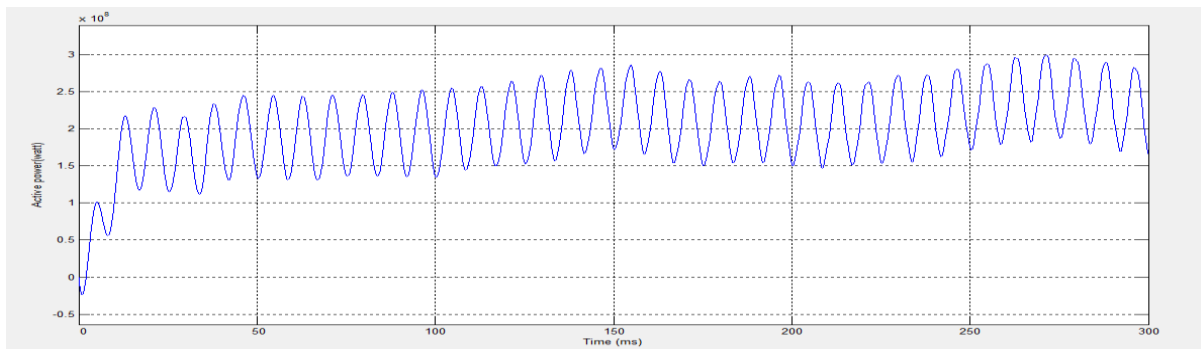Inverter side current

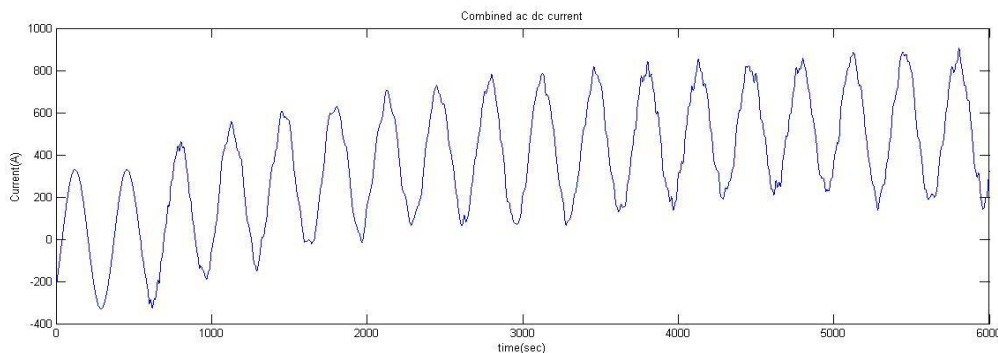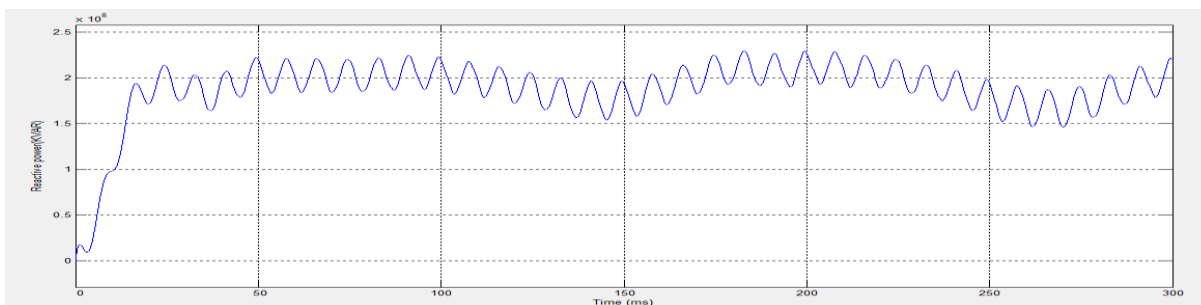Active power source side

Reactive power source side

Active power

Reactive power

VI. CONCLUSIONS

The feasibility to convert ac transmission line to a composite ac–dc line has been demonstrated. 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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