International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 2 Issue 10, October - 2013

# Power Upgrading of Transmission Line by Limiting power angle with AC-DC Transmission

T.Kavitha M.TECH project associative,
N.Narendar Reddy, assistant professor SVEC-suryapet, nalgonda district, A.P.

*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 load ability 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 (EHV) transmission, flexible ac transmission system (FACTS), power system computer-aided design (PSCAD) simulation, 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 [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. 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 [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.

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. 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.

## 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. 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

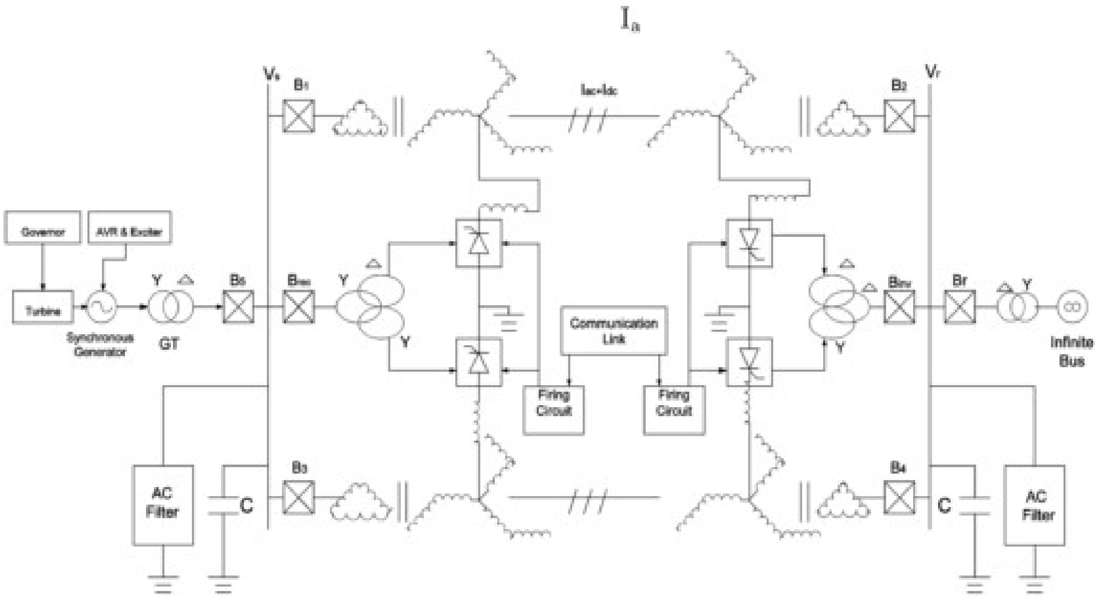


Fig. 1. Basic scheme for composite ac-dc transmission.

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 $(I_d/3)$ 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 $\alpha$, $\gamma$ 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

$$E_s = AE_R + BI_R \tag{1}$$

$$I_s = CE_R + DI_R \tag{2}$$

$$P_s + jQ_s = -E_sE_R^*/B^* + D^*E_S^2/B^* \tag{3}$$

$$P_R + jQ_R = E_s^*E_R/B^* - A^*E_R^2/B^*. \tag{4}$$

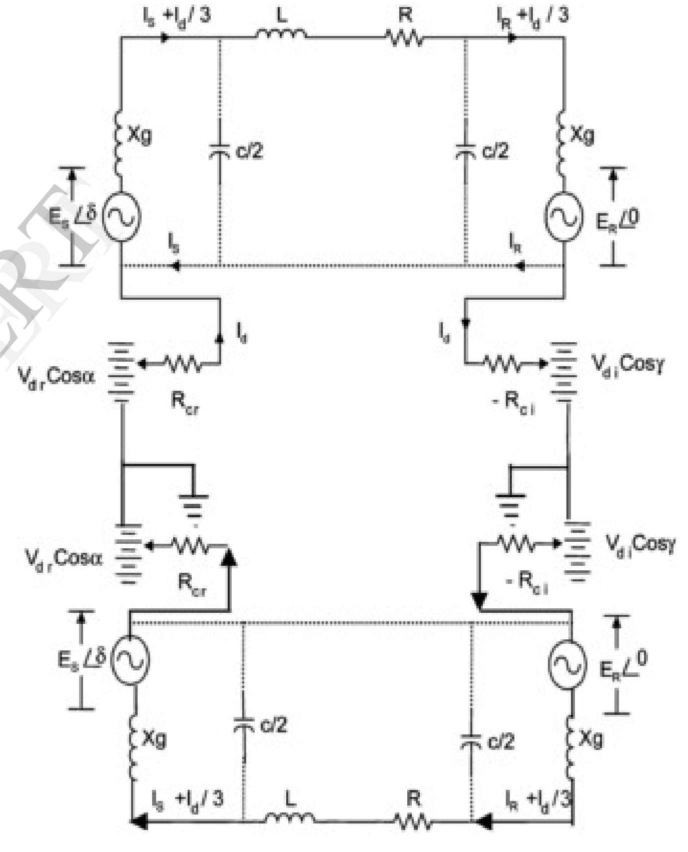


Fig. 2. Equivalent circuit.

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

$$P_{dr} = V_{dr}I_d \tag{5}$$

$$P_{di} = V_{di}I_d. \tag{6}$$

Reactive powers required by the converters are

$$Q_{dr} = P_{dr}\tan\theta_r \tag{7}$$

$$Q_{di} = P_{di}\tan\theta_i \tag{8}$$

$$\cos\theta_r = [\cos\alpha + \cos(\alpha + \mu_r)]/2 \tag{9}$$

$$\cos\theta_i = [\cos\gamma + \cos(\gamma + \mu_i)]/2. \tag{10}$$

$\mu_i$ and $\mu_r$ are commutation angles of inverter and rectifier, respectively, and total active and reactive powers at the two ends are

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

$$Q_{st} = Q_s + Q_{dr} \text{ and } Q_{rt} = Q_R + Q_{di}. \tag{12}$$

Transmission loss for each line is

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

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

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

Power loss for each line $= P_L \approx 3I^2R.$

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 $(I_{th})$

$$I_{th} = \left[I_a^2 + (I_d/3)^2\right]^{1/2}. \tag{14}$$

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

$$V_{max} = \sqrt{2}V_{ph} = V_d + \sqrt{2}V_a. \tag{15}$$

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 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 $V_{LL\,max} = \sqrt{6}V_a$. 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;

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

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

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

where $X$ is the transfer reactance per phase of the double circuit line, and $\delta_1$ is the power angle between the voltages at the two ends. To keep sufficient stability margin, $\delta_1$ is generally kept low for long lines and seldom exceeds 30°. With the increasing length of line, the loadability of the line is decreased [4]. An approximate value of $\delta_1$ may be computed from the loadability curve by knowing the values of surge impedance loading (SIL) and transfer reactance $X$ 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

$$P_{total} = P_{ac} + P_{dc} = 3V_a^2 \mathrm{Sin}\delta_2/X + 2V_dI_d. \tag{19}$$

The power angle $\delta_2$ 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, $P_{ac}$ 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

$$I_a = V(\mathrm{Sin}\delta/2)/X. \tag{20}$$

The rectifier dc current order is adjusted online as

$$I_d = 3\sqrt{I_{th}^{*2} - I_a^{*2}}. \tag{21}$$

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.

## III. DESCRIPTION OF THE SYSTEM MODEL

The network depicted in Fig. 1 was studied using PSCAD/EMTDC. 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]. It is equipped with an IEEE type

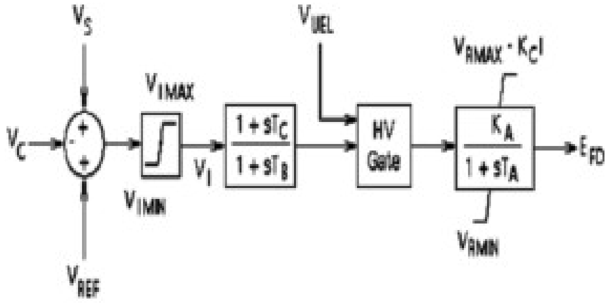


Fig. 3. IEEE type AC4A excitation system.

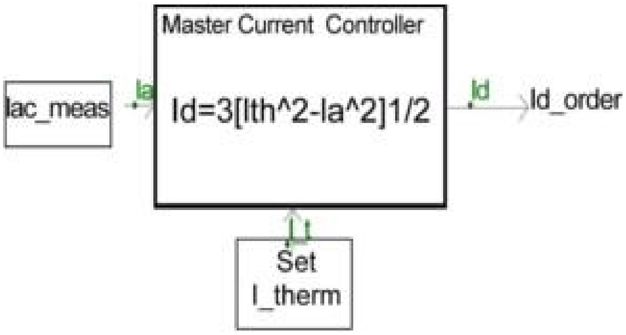


Fig. 4. Master current controller.

AC4A excitation system of which block diagram is shown in Fig. 3.

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 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 (VDCOL) 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 (PSCAD) 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 /extinction angle 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.

A master current controller (MCC), shown in Fig. 4, is used to control the current order for converters. . It measures the conductor ac current, computes the permissible dc current, and produces dc current order for inverters and rectifiers.

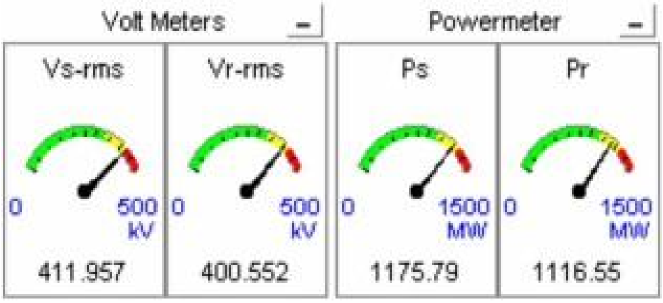


Fig. 5. Bus voltages and powers at sending and receiving ends.

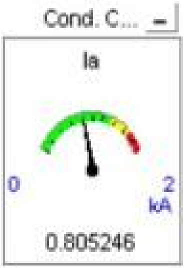


Fig. 6. Conductor ac current.

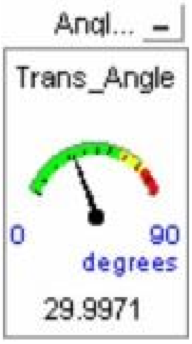


Fig. 7. Angle between buses.

## IV. CASE STUDIES: COMPUTATIONS AND SIMULATION

### A. AC Configuration Only

The loadability of Moose (commercial name), ACSR, twin bundle conductor, 400-kV, 50-Hz, 450-km double circuit line has been computed.

The parameters of the line are

$$z = 0.03252 + j0.33086\ \Omega/\mathrm{km/ph/ckt}.$$

$$y = j3.33797 \times 10^{-6}\ \mathrm{S/km/ph/ckt}.$$

Current carrying capacity of each subconductor $= 0.9\ \mathrm{kA}$

$I_{th} = 1.8\ \mathrm{kA/ckt}$. $\mathrm{SIL} = 511\ \mathrm{MW/ckt}$.

$M = 1.1$, ( [4]; $X = 74.4435\ \Omega/\mathrm{ph}$.

from loadability curve

Using (17)-(20), the computed power at receiving end and conductor current is

$$\mathbf{P_{total}} = \mathbf{1124.2\ MW};\ \delta_1 \approx \mathbf{30^\circ}$$

$$\mathbf{I_{ph/ckt}} = \mathbf{0.803\ kA}.$$

The simulated results in steady state are shown in Figs. 5-7.

TABLE I
COMPUTED RESULTS

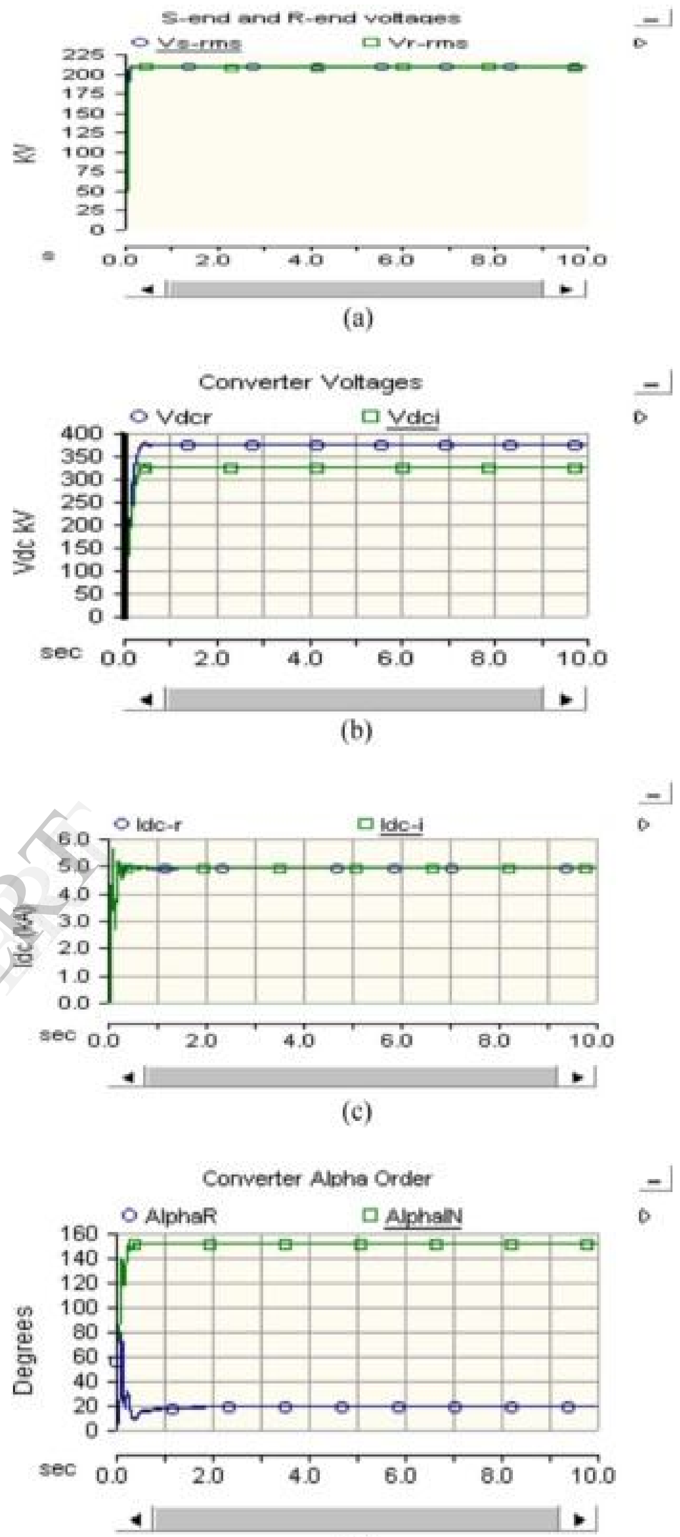
| Power Angle (δ) Degrees | $30^0$ | $45^0$ | $60^0$ | $75^0$ | $80^0$ |
|---|---|---|---|---|---|
| ac power(MW) $=3V_a^2\text{Sin}\delta_2/X$ | 290 | 410 | 502.61 | 560.6 | 571.55 |
| ac current $I_a$ (kA) $I_a = V(\text{Sin}\delta/2)/X$ | 0.4166 | 0.6122 | 0.805 | 0.98 | 1.035 |
| dc Current (kA) $I_d= 3\sqrt{I_{th}^{*2} - I_a^{*2}}$ | 5.253 | 5.078 | 4.829 | 4.529 | 4.418 |
| Dc Power $P_{dc}$=2Vdi x Idi (MW) | 1684.8 | 1624.9 | 1545.5 | 1149.44 | 1413.76 |
| **$P_{total}=P_{ac}+P_{dc}$ (MW)** | 1971 | 2034 | 2048 | 2010 | 1985 |

TABLE II
SIMULATED RESULTS

| Power Angle (δ) | **$30^0$** | **$45^0$** | **$60^0$** | **$75^0$** | **$80^0$** |
|---|---|---|---|---|---|
| Ps (MW) | 2306 | 2371.0 | 2381.3 | 2342.0 | 2318.380 |
| Pac (MW) Transfer | 294.89 | 411.00 | 495.3 | 541.86 | 548.43 |
| Pdc (MW) Transfer | 1715.5 | 1657.0 | 1585.8 | 1498.5 | 1467.0 |
| Pac_loss (MW) | 11.94 | 30.30 | 54.08 | 81.94 | 91.73 |
| Pdc_loss(MW) | 280.51 | 265.88 | 241.17 | 217.61 | 208.53 |
| Ploss_total( MW) | 292.45 | 296.18 | 295.25 | 299.55 | 300.26 |
| **Pr (MW) Total Transfer** | **1988.8** | **2051.14** | **2062.0** | **2019.36** | **1995.00** |
| Qs_line (MVAR) | -13.78 | 69.98 | 185.58 | 325.12 | 375.35 |
| Qr_line (MVAR) | 39.08 | 146.84<br>0 | 280.85 | 431.96 | 484.38 |
| Qrec (MVAR) | 883.6 | 884.36 | 885.29 | 878.1 | 869.48 |
| Qinv (MVAR) | 841.3 | 823.5 | 797.43 | 764.64 | 753.04 |
| ac current Ia (kA) | 0.41577 | 0.61123 | 0.79684 | 0.96952 | 1.02383 |
| dc current Id (kA) | 5.24263 | 5.1136 | 4.91185 | 4.6355 | 4.52512 |
| Cond. dc current Id/3 (kA) | 1.74754 | 1.70453 | 1.6373 | 1.5452 | 1.5084 |
| conductor current Isim(kA) | 1.78587 | 1.78264 | 1.78281 | 1.78641 | 1.78833 |
| Increase of power transfer | 76.94% | 82.49% | 83.451% | 79.66% | 77.5% |

The computed and simulated results are found to be in close conformity.

The conductor current 0.805246 kA is much below the thermal limit 1.8 kA.



(a)

(b)

(c)

(d)

Fig. 8. (a) Sending (Vs) and receiving (Vr) end bus voltages. (b) Rectifier (Vdcr) and inverter (Vdci) dc voltages. (c) Rectifier (Idc-r) and inverter (Idc-I) current. (d) Rectifier (AlphaR) and inverter (AlphaIN) firing angle.

### B. *Conversion of the Conventional Double Circuit AC Line Into Composite AC-DC Power Transmission Line*

Using (15) and (16)

$$V_a = 120\,\text{kV/ph}(208\,\text{kV}_{LL});\ V_d = 160\,\text{kV}.$$

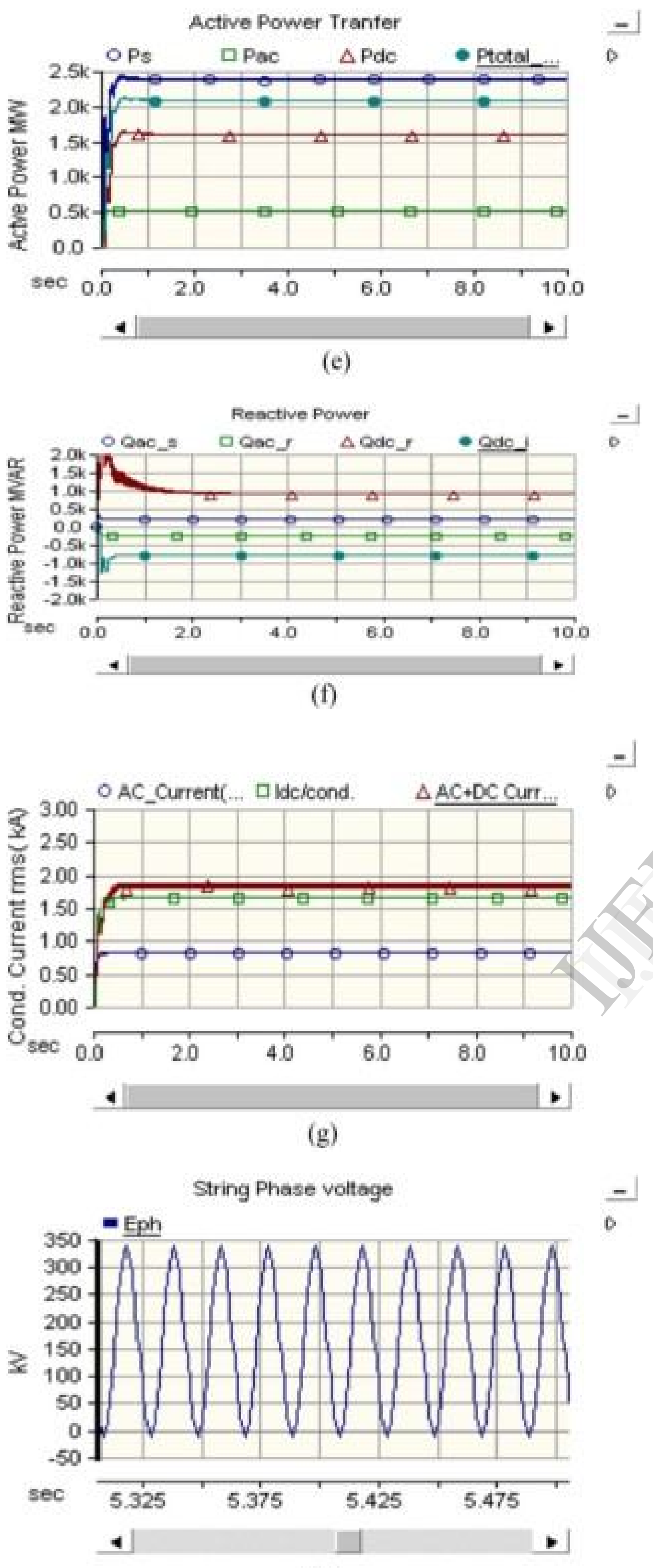


Fig. 8 (continued). (e) Sending end (Ps), ac (Pac), dc(Pdc), and total transfer (Ptotal_tr) power. (f) Line sending (Qac_s), receiving (Qac_s) end, rectifier (Qrec_dc), and inverter (Qinv_dc) reactive powers. (g) Ac, dc, and effective conductor current. (h) Phase voltage across insulator string.

The above ac voltage Va has been increased from 115.473 to 120 kV, and Vd has been decreased from 163.328 to 160.0 kV to have zero crossing in voltage wave.

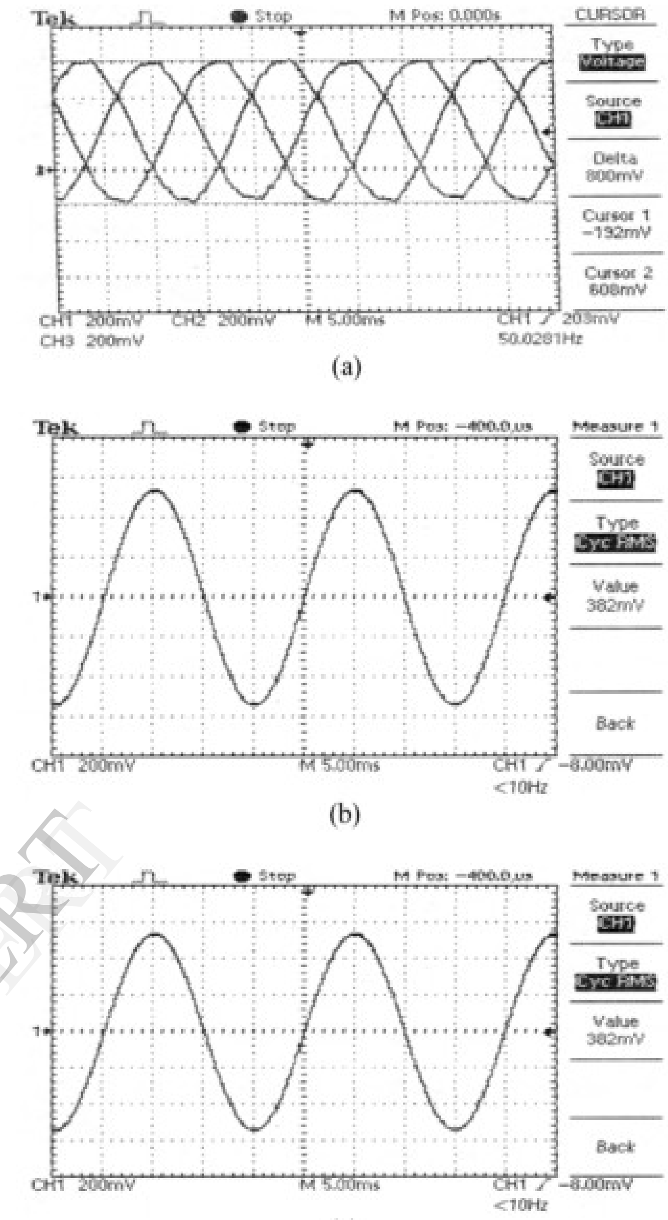


Fig. 9. (a) Phase to ground voltage with Vdc = 120 V. (Voltage Probe 200 mV=Div = 100 V=Div). (b) Transformer current without dc injection. (Current Probe 100 mV = 1 A). (c) Transformer current with dc injected via zig-zag connected neutral. (Current Probe 100 mV = 1 A).

is assumed to be maximum 80 , which is commonly used in lines controlled by FACTS devices [13].

The computed *approximate* power transfers for converted line at various transmission angles are shown in Table I.

The proposed composite ac-dc power scheme shown in Fig. 1 has been simulated in steady-state mode as a real system using PSCAD software package. The wattmeter and ammeter readings at various points on the system are tabulated in Table II.

Pdc_loss includes line loss due to dc current and converter losses. Pac_loss is line loss due to ac current only. The total power Pr at receiving end is the actual net power transfer after subtracting all losses like circuit breakers, transformers, etc.

It has been seen from computation as well as simulation that the maximum power transfer of 2062.0 MW transmitted by composite ac-dc line occurs at power angle of 60 . The same

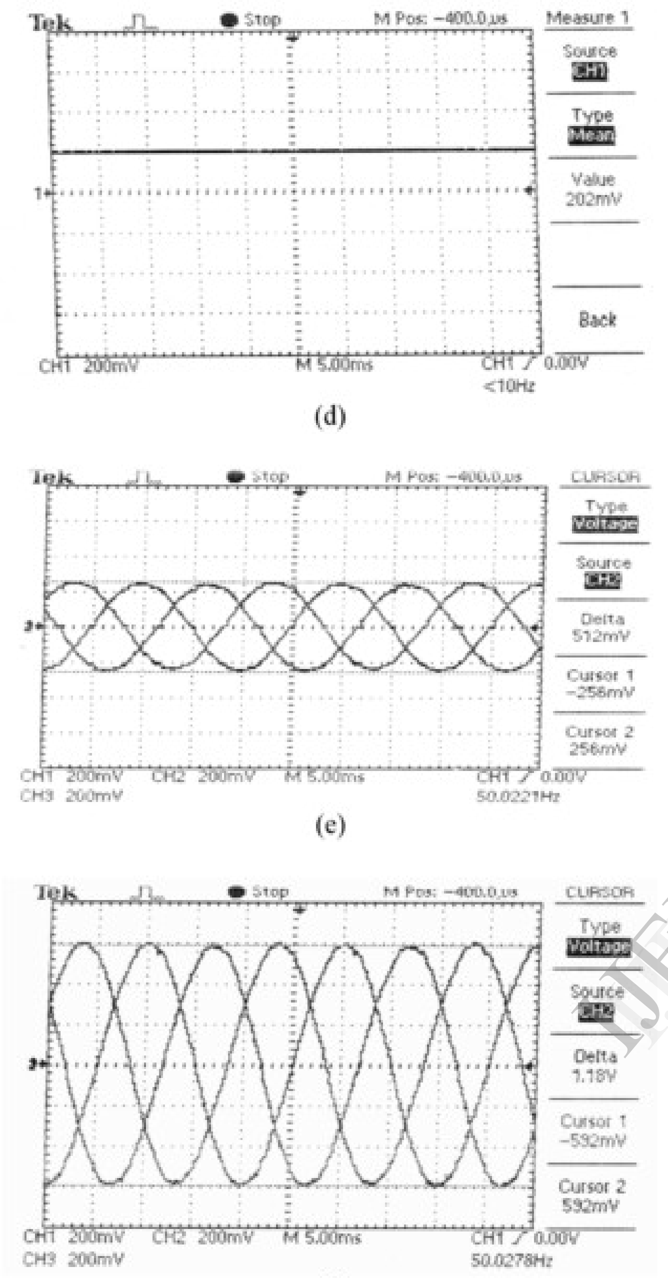


Fig. 9 (continued). (d) Smoothed Vdc_r with dc filter at rectifier ouput. (L = 23 mH. C = 1000 micro F). (Voltage Probe 200 mV=Div = 100 V). (e) Ac voltage at input to rectifier (ELL). (Voltage Probe 0:2 V=Div = 100 V). (f) Conductor line to line voltage (VL). (Voltage Probe 0:2 v = 100 V).

amount of power transfer through conventional double circuit line would require a power angle of 73.68 , which is beyond the safe limit for power angle. The corresponding conductor current is 1.7744 kA. $(I_{ph/ckt})$

Fig. 8 shows the time response of various system performances at power angle of 60.

It has been observed from above tracing that system is stable even after superimposing dc on ac.

## V. EXPERIMENTAL VERIFICATION

The feasibility of the conversion of the ac line to composite ac-dc line was verified in a laboratory-size model. The basic objective was to verify the operation of the transformers, particularly, the effect on core saturation, with the superimposed ac-dc current flow and the power flow control.

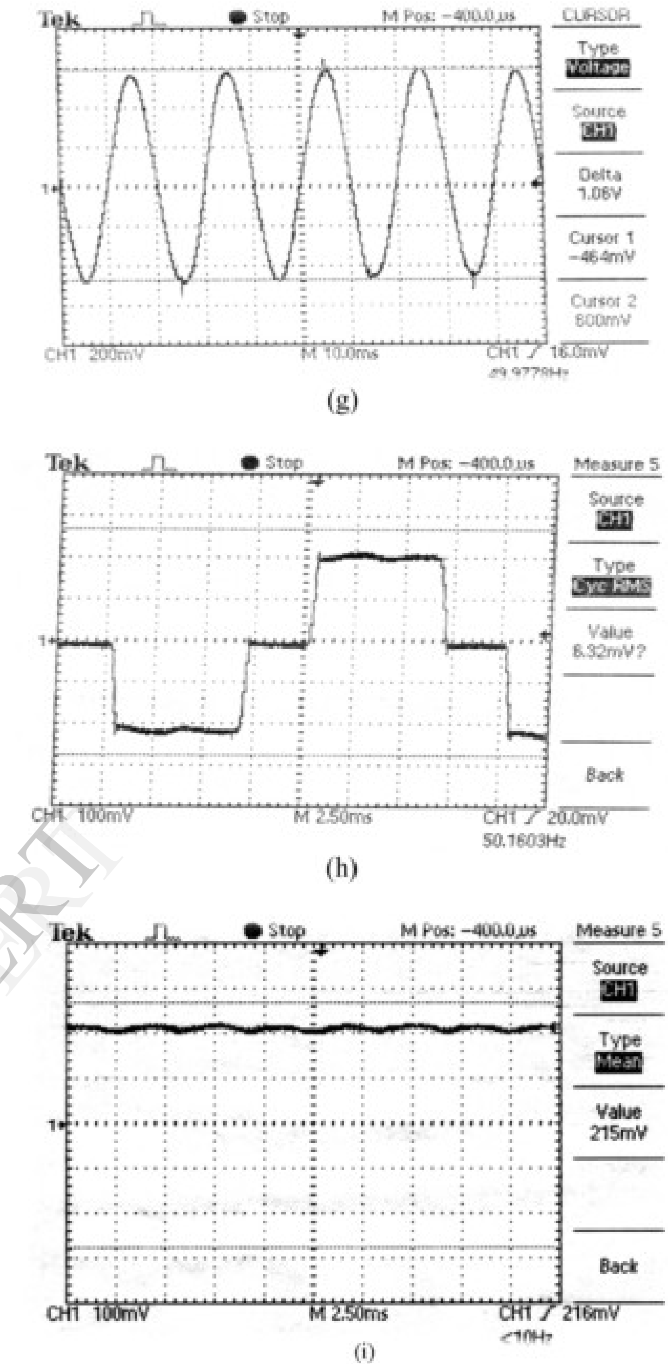


Fig. 9 (continued). (g) Simultaneous ac-dc current in Phase A. (Current Probe 100 mV = 1 A). (h) Rectifier ac input line current (ILL) in Phase A. (Current probe 100 mV = 1 A). (i) Rectifier dc current (Idcr). (Current probe 100 mV = 1 A).

The transmission line was modeled as a three-phase -network having $L = 83$ mH and $C = 0.5$ $\mu$F. Transformers having a rating of 6 KVA, 400/75/75 Volts were used at each end. The secondary of these transformers were connected in zig-zag fashion. A supply of 3-ph, 400 V, 50 Hz was given at the sending end and 400 V, 0-5.25 kW variable resistive load was connected at the receiving end. A 10-Amp, 23-mH dc reactor $(X_d)$ was used at each end with the 230 V zig-zag connected neutral. Two identical line-commutated six-pulse bridge converters were used for rectifier and inverter. The dc voltages of rectifier and inverter bridges were adjusted to vary dc current between 0 to 6 A. Ac filters were not connected at converter ac buses.

The power transmission with and without dc component was found to be satisfactory. There was no saturation of the transformers core with and without dc component.

Experimental results for 3-A ac current with superimposed 2/3-A dc current in each line are depicted in Fig. 9.

The shape and magnitude of primary current of the zig-zag connected transformer remains unchanged with and without injection of dc current as shown in Fig. 9(b) and Fig. 9(c). Fig. 9(f)
shows the wave shape of line-line voltage, which has no dc offset as theoretically predicted. Rectifier input ac current is stepped shaped as no filters has been connected on ac side as shown in Fig. 9(h).

## VI. 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 loadability 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 stimes the ac voltage before conversion, respectively. $1/\sqrt{2}$

## REFERENCES

[1] L. K. Gyugyi, "Unified power flow concept for flexible A.C. transmission system," *Proc. Inst. Elect. Eng.*, p. 323, Jul. 1992.

[2] L. K. Gyugyi *et al.*, "The unified power flow controller; a new approach to power transmission control," *IEEE Trans. Power Del.*, vol. 10, no.2, pp. 1085-1097, Apr. 1995.

[3] N. G. Hingorani, "FACTS—flexible A.C. transmission system," in *Proc. Inst. Elect. Eng. 5th. Int. Conf. A.C. D.C. Power Transmission*,London, U.K., 1991.

[4] P. S. Kundur, *Power System Stability and Control*. New York: McGraw-Hill, 1994.

[5] K. P. Basu and B. H. Khan, "Simultaneous ac-dc power transmission," *Inst. Eng. (India) J.-EL*, vol. 82, pp. 32-35, Jun. 2001.

[6] H. Rahman and B. H. Khan, "Enhanced power transfer by simultaneous transmission of AC-DC: a new FACTS concept," in *Proc. Inst. Elect. Eng. Conf. Power Electronics, Machines, Drives*, Edinburgh, U.K., Mar. 31-Apr. 2 2004, vol. 1, pp. 186-191.

[7] A. Clerici, L. Paris, and P. Danfors, "HVDC conversion of HVAC line to provide substantial power upgrading," *IEEE Trans. Power Del.*, vol.6, no. 1, pp. 324-333, Jan. 1991.

[8] Padiyar, *HVDC Power Transmission System*. New Delhi, India: Wiley Eastern, 1993.

[9] E. W. Kimbark, *Direct Current Transmission*. New York: Wiley, 1971, vol. I.

[10] J. Arillaga and N. R. Watson, *Computer Modelling of Electrical Power Systems*. Chichester, U.K.: Wiley, 2003.

[11] M. A. Chaudhry and D. P. Caroll, "Coordinated active and reactive power modulation of multiterminal HVDC system," *IEEE Trans. Power App. Syst.*, vol. PAS-103, pp. 1480-1485, 1989.

[12] K. R. Padiyar, M. A. Pai, and C. Radhakrishna, "Analysis of D.C. link control for system stabilization," in *Proc. Inst. Elect. Eng. Conf. Publ. No. 205*, London, U.K., 1981, pp. 145-148.

[13] M. Stella, P. K. Dash, and K. P. Basu, "A neuro-sliding mode controller for STATCOM," *Elect. Power Compon. Syst.*, vol. 32, pp. 131-147, Feb. 2004.

[14] M. Szechtman, T. Wees, and C. V. Thio, "First benchmark model for HVDC control studies," *Electra*, no. 135, pp. 54-67, Apr. 1991.

[15] PSCAD/EMTDC, User's Guide, Manitoba-HVDC Research Centre. Winnipeg, MB, Canada, Jan. 2003.