Introducing the Family of "Sen" Transformers: A Set of Power Flow Controlling Transformers

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***Abstract*—Real and Reactive power flow in an alternating current transmission line are independently controlled by connecting, to the transmission line, a series-compensating voltage, which is variable in magnitude and at variable angle with respect to the transmission line voltage as well as the prevailing line current. The traditional technology of transformer and tap changer is used to implement this novel technique. An additional voltage regulation capability can also be implemented. The speed of tap changer operation determines the response time of this power flow controller, which is quite adequate in most utility applications. The response time can be improved if suitable solid-state switches are available to replace the mechanical taps.**

***Index Terms*—Power transmission control, Load flow control, Power transmission, Power transformers, Phase shifters, Power electronics, Converters, FACTS, UPFC, etc.**

I. Introduction

ELECTRIC power flow through an alternating current transmission line is a function of the line impedance (R, X_L), the magnitudes of the sending-end voltage, $\mathbf{V_s}$, and the receiving-end voltage, $\mathbf{V_r}$, and the phase angle, δ, between these voltages as shown in Fig. 1(a). The expressions for power flow at the receiving-end of the line are shown, considering the line is represented in its simplest form with a reactance, X_L. The voltage, $\mathbf{V_X}$, across the transmission line is the difference between the sending- and receiving-end voltages and leads the line current, $\mathbf{I}$, by 90^o as shown in Fig. 1(b).

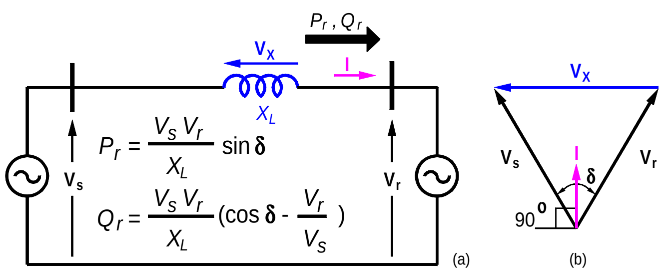

Fig. 1. (a) Power transmission system and (b) phasor diagram

The direct method of voltage regulation of a transmission line is to add a compensating voltage vectorially in- or out-of-phase with the voltage of the transmission line at the point of connection [1]. There are other ways to regulate the line voltage as well. The indirect way to regulate the line voltage is to connect a variable capacitor or a variable inductor in shunt with the transmission line. A shunt-connected capacitor raises the line voltage with its generated reactive power. A shunt-connected inductor absorbs reactive power from the line and lowers the line voltage. Through the use of a *Static Var Compensator* (SVC) [2], a shunt-connected variable capacitor or a variable inductor is implemented.

Also, the indirect way to implement a variable shunt capacitor or a variable shunt inductor is to generate a variable magnitude compensating voltage in phase with the line voltage at the point of connection and to connect the compensating voltage in shunt with the line through an inductor. Through control action, the magnitude of the compensating voltage can be made higher or lower than the line voltage in order to emulate a variable capacitor or a variable inductor. Through the use of a *STATic synchronous COMpensator* (STATCOM) [3, 4], a variable magnitude shunt-connected voltage source is implemented.

The effective phase angle of a transmission line voltage is varied by using a Phase Shifting Transformer, which is also known as a Phase Angle Regulator (PAR) [5].

Changing one parameter (voltage or angle) using a power flow controller affects both the real and the reactive power flow in the transmission line simultaneously. The key to be able to control the flow of real power, P_r, and reactive power, Q_r, in a line to be a particular pair of values is to modify the sending-end voltage to be of one particular magnitude and at a particular angle. A series-connected compensating voltage can modify the sending-end voltage. For a desired amount of real and reactive power flow in the line, the compensating voltage has to be of one particular magnitude and at a particular angle with respect to the line voltage. The compensating voltage is also at any angle with the prevailing line current and, therefore, emulates in series with the transmission line a capacitor that increases the power flow of the line or an inductor that decreases the power flow of the line and a positive resistor that absorbs real power from the line or a negative resistor that delivers real power to the line. Therefore, the desired compensating voltage is actually an impedance emulator. Through the use of a *Unified Power Flow Controller* (UPFC) [6, 7], a variable series-impedance is emulated.

The Voltage-Sourced Converter (VSC)-based UPFC has the capability of providing the fast dynamic response, but may not be justified economically for the use in a utility environment

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where the need is to regulate the line voltage and the power flow in the line in a “slow” manner. The proposed family of “Sen” Transformers, which is based on a single-core, three-phase transformer and tap changers, provides voltage regulation at a point in a transmission line in addition to the independent power flow control in the transmission line by using reliable, traditional, and thus less expensive technology. It also gives users a futuristic option to choose the dynamic response of the compensation scheme. If a faster response is needed, the tap changer may be implemented with suitable solid-state switches. Otherwise, the dynamic response is limited by the speed of the mechanical tap changer. The objective in this paper is to describe the evolution of the new family of “Sen” Transformers.

II. Background

The effect of a series-connected compensating voltage on the power flow in a transmission line is as follows.

A. Direct Method of Voltage Regulation

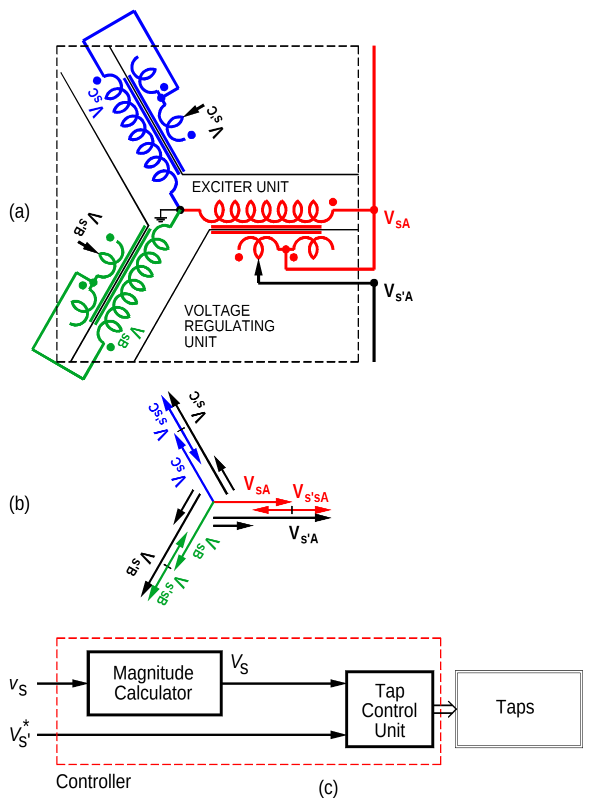

Fig. 2. (a) Voltage regulator circuit, (b) phasor diagram, and (c) controller

In order to regulate the voltage at any point in a transmission line, an in-phase or an out-of-phase voltage is connected in series with the line. Fig. 2(a) shows a voltage regulator scheme for regulating the voltage at any point in a transmission line. The exciter unit consists of a three-phase Y-connected primary winding, which is impressed with the line voltage, $\mathbf{V}_s$. The voltage-regulating unit consists of a total of six secondary windings (two windings in each phase for a bipolar voltage connection). The line is regulated at a voltage, $\mathbf{V}_{s'}$, by adding a compensating voltage, $\mathbf{V}_{s's}$, either in- or out-of-phase with the line voltage, $\mathbf{V}_s$. The corresponding phasor diagram is shown in Fig. 2(b). The bipolar compensating voltage in any phase is induced, through autotransformer action, in two windings placed on the same phase of the transformer core. The controller, as shown in Fig. 2(c), is fed with two input signals – one is the exciting line voltage, v_s, and the other is the reference voltage, $V_{s'}$*. The tap control unit, in the controller, monitors the magnitude of the exciting voltage, V_s, and the reference voltage, $V_{s'}$*, and turns on the appropriate tap, in the voltage-regulating unit, in order to regulate the line voltage at $V_{s'}$*.

Fig. 3 shows the schematic diagram of a thyristor-controlled tap changer [8]. A transformer winding is tapped at various places. Each of the tapped points is connected to one side of a back-to-back thyristor (triac) switch. The other side of each thyristor switch is connected together at point A. Depending on which thyristor is on, the voltage between points A and B can be varied between zero and the full-winding voltage with desired steps in between. In the mechanical version of this arrangement, a load tap changer connects with one of various taps to give a variable number of turns between the connected tap and one end of the winding.

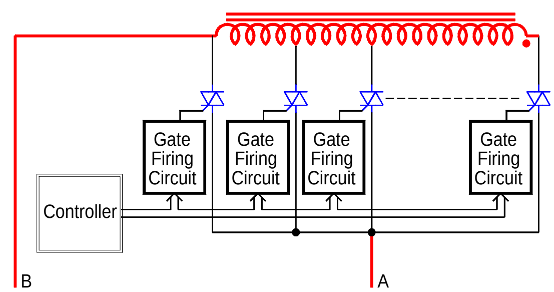

Fig. 3. Thyristor-controlled tap changer

B. Phase Angle Regulation

A Phase Angle Regulator (PAR) connects a voltage in series with the transmission line and in quadrature with the phase-to-neutral voltage of the transmission line as shown in Fig. 4(a). The series-connected compensating voltage introduces a phase shift, ε, [Fig. 4(b)] whose magnitude (for small change) in radian varies with the magnitude of the compensating voltage in pu where the phase-to-neutral voltage of the transmission line is the base voltage.

In a typical configuration, a PAR consists of two transformers as shown in Fig. 4(a). The first transformer (exciter unit) is called a regulating transformer and is connected in shunt with the line. Its primary windings are excited from the line voltage ($\mathbf{V}_s$) and a three-phase bipolar voltage is induced in the secondary windings. With the use of taps, a compensating voltage ($\mathbf{V}_{s's}$) with variable magnitude and in quadrature with the line voltage is generated from the phase-to-phase voltage of the induced voltage of the regulating transformer. For series connection of this voltage, an electrical isolation is necessary. The second transformer (series unit) is called a series transformer and is excited from the phase-to-phase voltage of the regulating transformer. The induced voltage of the series transformer is connected in series with the line. If the series transformer is a step-down transformer, the primary windings of the series transformer as well as the secondary windings of the regulating transformer are high voltage- and low current rated so that the taps on the secondary side of the regulating transformer can operate at a low current and can ride through a high fault current. Please note that a PAR can be realized with a single-core transformer as well. In this case, the taps are always subject to carry high line current as well as even higher fault current.

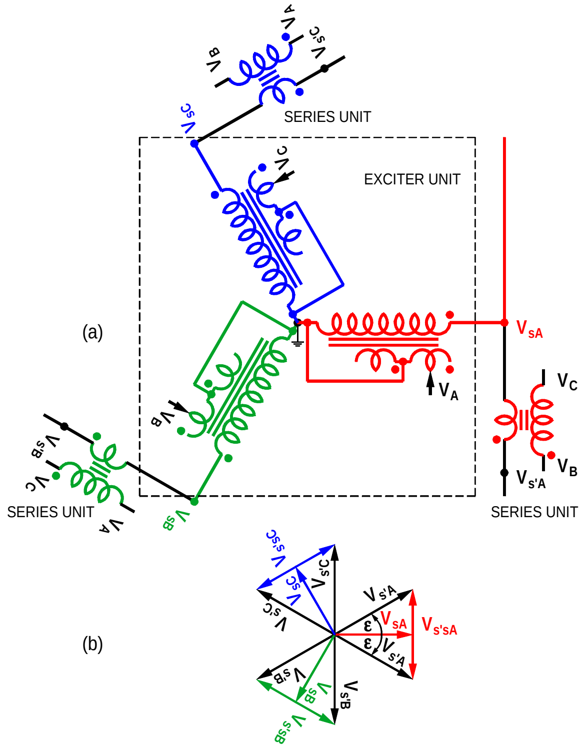

Fig. 4. (a) Phase angle regulator circuit and (b) phasor diagram

C. Series Reactance Emulation

In a special case, the sending-end voltage magnitude and its phase angle can also be varied together in such a way so that the effective line reactance is changed. The direct way to regulate the effective line reactance is to connect a capacitor or an inductor in series with the transmission line. A series-connected capacitor increases the power flow in the line by decreasing the effective line reactance between its two ends. A series-connected inductor decreases the power flow in the line by increasing the effective line reactance between its two ends. Through the use of a *Thyristor-Controlled Series Compensator* (TCSC) [9], a series-connected variable capacitor or a variable inductor can be implemented. Also, the indirect way to implement a variable series capacitor or a variable inductor is to connect a variable magnitude compensating voltage in series with the line and in quadrature with the line current. Through control action, the magnitude of the compensating voltage can be varied and made lagging or leading the prevailing line current in order to emulate a variable capacitor or a variable inductor. Through the use of a *Static Synchronous Series Compensator* (SSSC) [10, 11], a variable magnitude series-connected compensating voltage source is implemented.

Fig. 5 shows a simple power transmission system with an SSSC operated both in inductive and in capacitive modes and the related phasor diagrams. The line current, **I**, decreases [Fig. 5(c)] from its uncompensated value [Fig. 5(b)] when the series-connected compensating voltage, $\mathbf{V_q}$, in load convention, leads the line current by 90^o to provide inductive reactance compensation. The line current, **I**, increases [Fig. 5(d)] when the series-connected compensating voltage, $\mathbf{V_q}$, lags the line current by 90^o to provide capacitive reactance compensation. The expressions for power flow at the receiving-end of the line are shown considering the modified sending-end voltage is $\mathbf{V_{s'}}$.

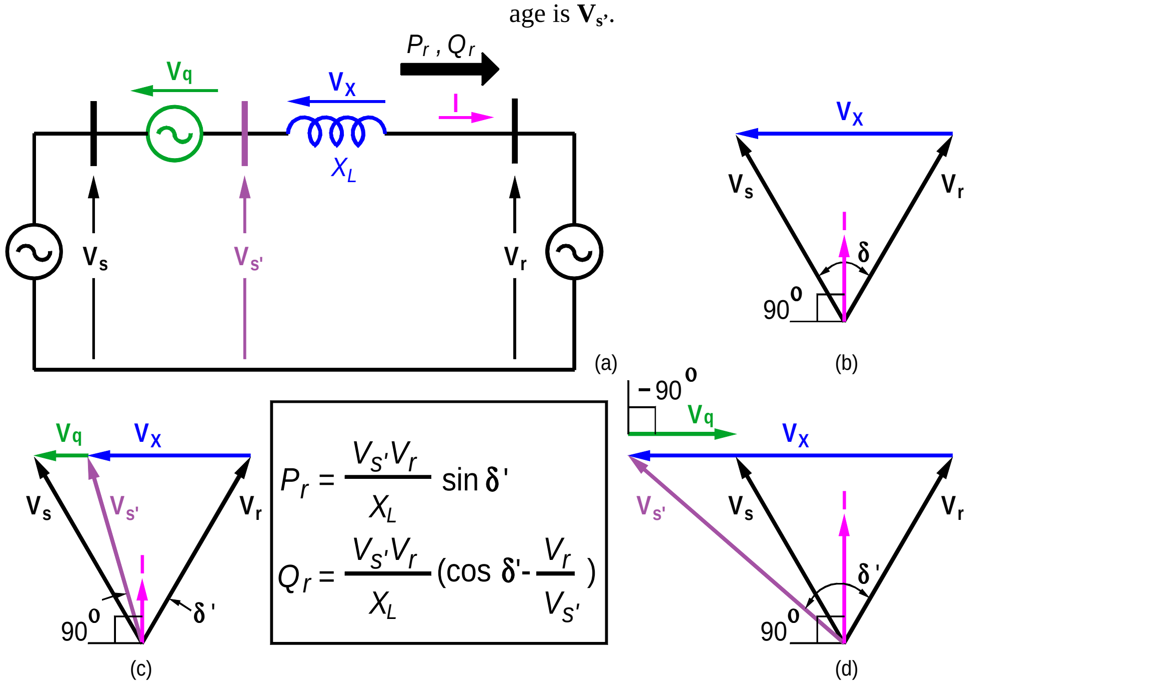

Fig. 5. (a) Power transmission system and its series reactance emulator with a compensating voltage, $\mathbf{V_q}$, and phasor diagrams for (b) uncompensated line (c) inductively-compensated line, and (d) capacitively-compensated line.

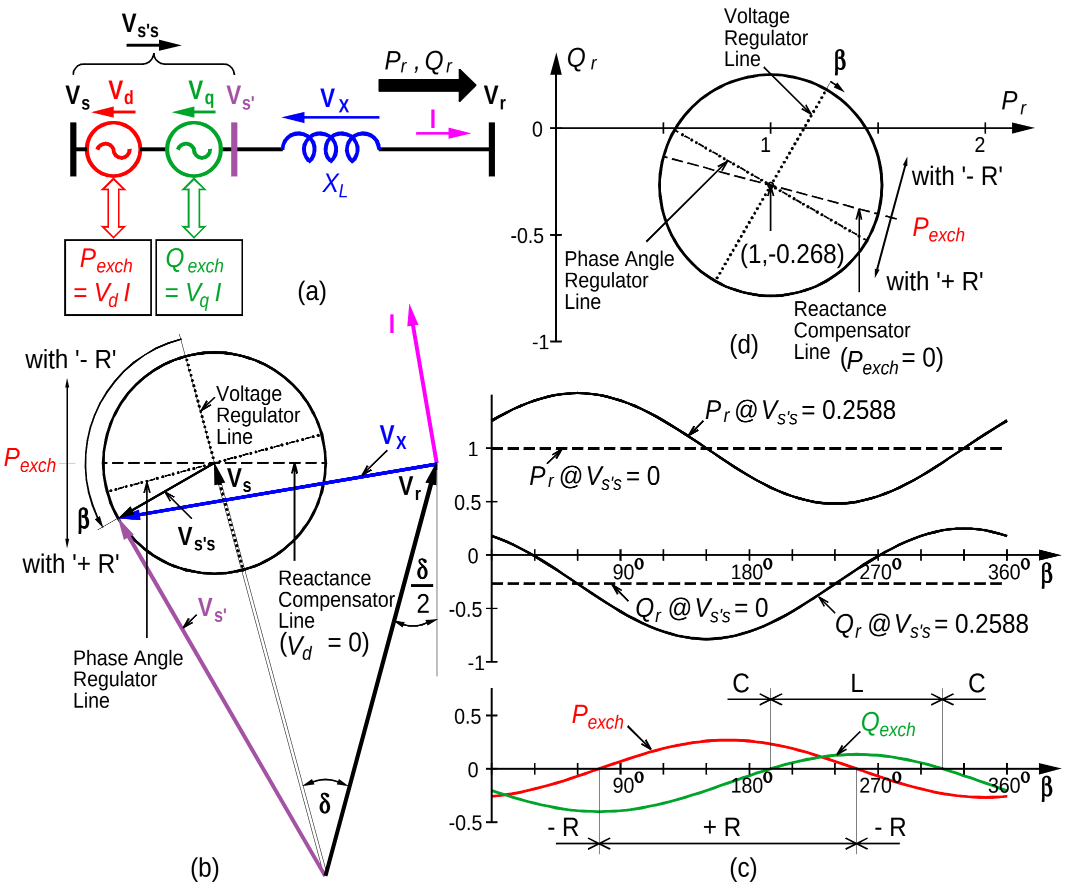

Fig. 6. Effect of a series-connected voltage source on power flow in a transmission Line. (a) Power transmission system with a series-connected compensating voltage, $\mathbf{V_{s's}}$, (b) phasor diagram, (c) variation of the receiving-end real and reactive power (P_r and Q_r) and the exchanged compensating real and reactive power as a function of the angular rotation of the compensating voltage phasor, and (d) receiving-end Q_r vs. P_r.

D. An Ideal Series-Connected Power Flow Controller

The effect of a series-connected variable magnitude and variable angle compensating voltage on the power flow in a transmission line is shown in Fig. 6. A simple power transmission system with a sending-end voltage, $\mathbf{V_s}$, a receiving-end voltage, $\mathbf{V_r}$, the voltage, $\mathbf{V_X}$, across line reactance, X_L and the compensating voltage, $\mathbf{V_{s's}}$, is shown in Fig. 6(a). For simplicity, it is considered that $V_s = V_r = 1$ pu, the angle between them to be $\delta = 30^o$, and $X_L = 0.5$ pu. When the transmission line is uncompensated, the real power flow in the line is 1 pu and the reactive power flow at the receiving-end is 0.268 pu capacitive. The voltage across the transmission line is the difference between the sending- and receiving-end voltages and it is 0.5176 pu. Fig. 6(b) shows the phasor diagram related to a series-connected compensating voltage with a fixed magnitude of 0.2588 pu and its entire controllable range of $0 \leq \beta \leq 360^o$. The compensating voltage, $\mathbf{V_{s's}}$, is added to the fixed sending-end voltage, $\mathbf{V_s}$, to produce the *effective* sending-end voltage, $\mathbf{V_{s'}} = \mathbf{V_s} + \mathbf{V_{s's}}$. The difference, $\mathbf{V_{s'}} - \mathbf{V_r}$, provides the *compensated* voltage, $\mathbf{V_X}$, across X_L. As the angle, β, is varied over its full 360^o range, the end of phasor, $\mathbf{V_{s's}}$, moves along a circle with its center located at the end of phasor, $\mathbf{V_s}$. The rotation of phasor, $\mathbf{V_{s's}}$, with angle, β, modulates both the magnitude and the angle of phasor, $\mathbf{V_X}$. The real power, P_r, and the reactive power, Q_r, at the receiving-end vary with angle, β, in a sinusoidal manner as shown in Fig. 6(c). The compensating voltage, $\mathbf{V_{s's}}$, is at any angle with the prevailing line current, $\mathbf{I}$, and, therefore, exchanges, with the line, both real power, P_{exch} (= $V_d I$), and reactive power, Q_{exch} (= $V_q I$), where $\mathbf{V_d}$ and $\mathbf{V_q}$ are the respective real or direct and reactive or quadrature components of the compensating voltage with load convention. These exchanged real power, P_{exch}, and reactive power, Q_{exch}, are also sinusoidal functions of angle, β, as shown in Fig. 6(c). For a given magnitude of a compensating voltage, the exchanged capacitive power, Q_{exch}, is larger than its inductive counterpart due to the fact that the capacitive compensation produces a larger line current. The compensating voltage, being at any angle with the prevailing line current, emulates in series with the line a capacitor (C) or an inductor (L) and a positive resistor (+R) or a negative resistor (-R).

The real and reactive power flow in the line can be controlled within the range defined by the *P-Q* plot of Fig. 6(d) by choosing the magnitude, $V_{s's}$, and angle, β, of the compensating voltage, $\mathbf{V_{s's}}$, between 0 and 0.2588 pu and between 0 and 360^o, respectively. In special cases [Fig. 6(b)], the following occur.

- A compensating voltage can be in- or out-of-phase with the phase-to-neutral voltage of the transmission line to implement a voltage regulator.

- A compensating voltage can be in quadrature with the phase-to-neutral voltage of the transmission line to implement a phase angle regulator.
- A compensating voltage can be such that it provides series reactance compensation because of being in quadrature with the prevailing line current. If the circular controllable area is equally divided by the reactance compensator line (V_d = 0 or P_{exch} = 0), the upper and lower halves represent P_{exch} due to '-R' and '+R', respectively.

Any compensator, which provides compensation for one of the transmission line parameters (voltage, angle or reactance) operates on a set of linear operating points inside the *P*-*Q* circle as defined above. Since these operating characteristic lines are neither horizontal nor vertical in the *P*-*Q* plane, changing one parameter with the use of these compensators changes both the real and the reactive power flow in the transmission line simultaneously as shown in Fig. 6(d).

The magnitude and the angle of the effective sending-end voltage, $\mathbf{V}_{s'}$, can be regulated with the use of a voltage regulator and a phase angle regulator, respectively. In order to implement both of these functions combined, it requires the use of one or more transformers with certainly more than the necessary number of windings. It would be advantageous to use a scheme, which is based on a single-core, three-phase transformer and tap changers in order to generate the required compensating voltage, $\mathbf{V}_{s's}$, which modifies the effective sending-end voltage, $\mathbf{V}_{s'}$. This new scheme requires the use of minimum number of windings.

III. A New Voltage Regulator

The new voltage regulator [12] connects a compensating voltage, $\mathbf{V}_{s's}$, of line frequency in series with the line, through autotransformer action, in order to regulate the voltage at a point in a transmission line. As shown in Fig. 7(a), the voltage, $\mathbf{V}_s$, at any point in the electrical system is applied to a shunt-connected single-core, three-phase transformer's primary windings. A total of nine secondary windings (a1, c2, and b3 on the core of A-phase, b1, a2, and c3 on the core of B-phase, and c1, b2, and a3 on the core of C-phase) constitute the voltage-regulating unit. By choosing the number of turns of any winding and by using a tap, the magnitude of the compensating voltage in that winding can be varied between zero and the maximum voltage that the winding can induce.

The bipolar compensating voltage, $\mathbf{V}_{s's}$, [Fig. 7(b)] in any phase is derived from the phasor sum of the voltages induced in a three-phase winding set (a1, a2, and a3 for connection in A-phase, b1, b2, and b3 for connection in B-phase, and c1, c2, and c3 for connection in C-phase). The in-phase component of the compensating voltage for any phase is induced in a winding that is placed on the corresponding phase of the transformer core. The out-of-phase component of the compensating voltage for that phase is derived from the phasor sum of the voltages induced in two equal-turn windings, which are placed on the remaining two phases of the transformer core. For example, the in-phase component of the compensating voltage for the A-phase is induced in a winding that is placed on the core with the exciting primary winding of the A-phase. The out-of-phase component of the compensating voltage for the A-phase is derived from the phasor sum of the voltages induced in two equal-turn windings, which are placed on the core with the exciting primary windings of the B-phase and the C-phase, respectively. The effect is such that the transmission line voltage at a point is regulated.

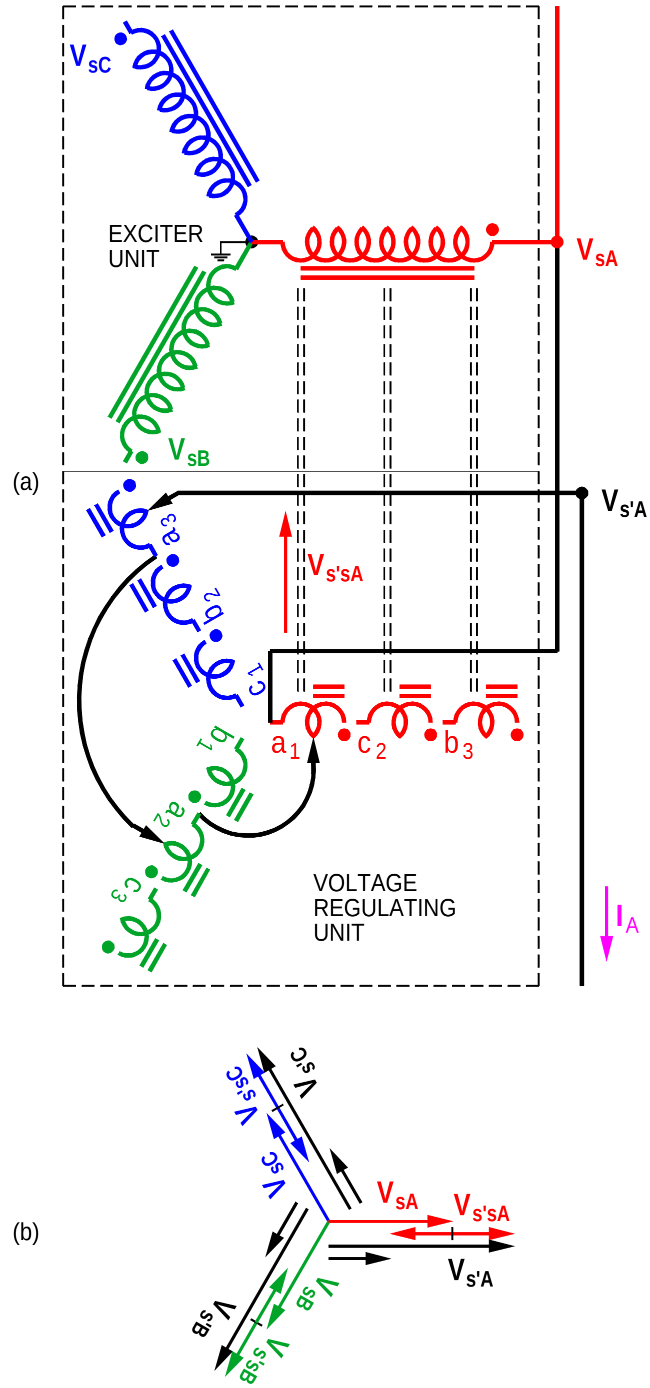

Fig. 7. (a) Voltage regulator circuit and (b) phasor diagram

This new voltage regulation scheme can be extended for a multiline transmission system where a number of series compensating voltages, one for each line, can be generated by placing the exciting three-phase primary windings and a number of secondary nine-winding sets on the same core.

IV. A New Impedance Regulator

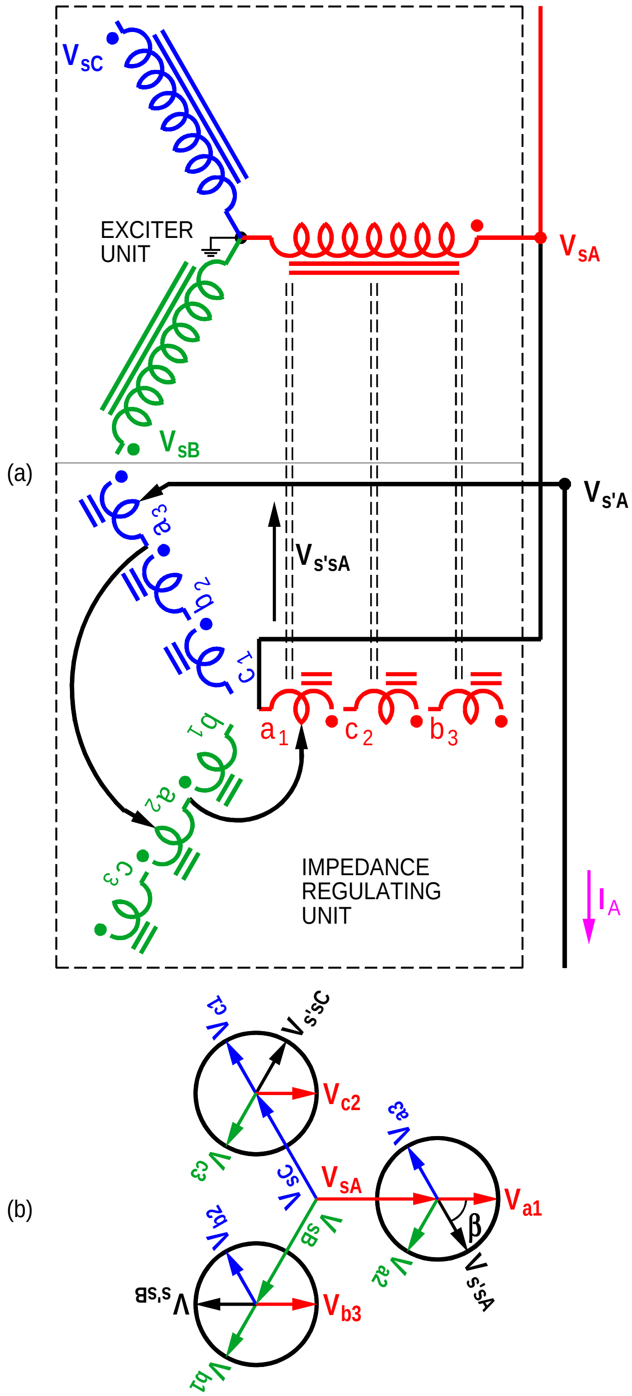

Fig. 8. (a) Impedance regulator circuit and (b) phasor diagram

The new impedance regulator [12] connects a compensating voltage, $\mathbf{V}_{s's}$, of line frequency in series with the line through autotransformer action, which modifies the effective sending-end voltage, $\mathbf{V}_{s'}$, in order to independently control the real and reactive power flow of the line. As shown in Fig. 8(a), the voltage, $\mathbf{V}_s$, at any point in the electrical system is applied to a shunt-connected single-core, three-phase transformer's primary windings. A total of nine secondary windings (a1, c2, and b3 on the core of A-phase, b1, a2, and c3 on the core of B-phase, and c1, b2, and a3 on the core of C-phase) constitute the impedance-regulating unit.

By choosing the number of turns of each of the three windings, and therefore the magnitudes of the components of the three 120^o phase-shifted induced voltages, the compensating voltage in any phase is derived from the phasor sum of the voltages induced in a three-phase winding set (a1, a2, and a3 for connection in A-phase, b1, b2, and b3 for connection in B-phase, and c1, c2, and c3 for connection in C-phase). Fig. 8(b) shows the phasor diagram relating the line voltage, $\mathbf{V}_s$, and the compensating voltage, $\mathbf{V}_{s's}$, with its components. The compensating voltage can be at any angle with the prevailing line current. The real or direct component of the compensating voltage provides the series resistance emulation; whereas the reactive or quadrature component provides the series reactance emulation. The effect of impedance emulation is such that the real and the reactive power flow in a transmission line can be regulated independently. Please note that the power circuit is identical for both the voltage regulator and the impedance regulator. Therefore, both functions of voltage regulation and independent real and reactive power flow control can be implemented in just one unit by proper programming of the tap control unit. Notably, each of a1, b1, and c1 is tapped at the same number of turns; each of a2, b2, and c2 is tapped at the same number of turns; each of a3, b3, and c3 is tapped at the same number of turns. However, the number of turns in the a1-b1-c1 set, a2-b2-c2 set, and a3-b3-c3 set can be different from each other.

V. Limited Angle Operation Of The New Impedance Regulator

An impedance regulator requires the use of a single-core three-phase transformer with three primary windings and nine secondary windings. The compensating voltage, $\mathbf{V}_{s's}$, is of variable magnitude and at a variable angle. However, in many instances, the capability of connecting a voltage in series with a line within its entire range of 360^o is not needed. In this case, the circuit configuration can be simplified [12].

Figs. 9–12 show, through autotransformer action, the generation of a line frequency compensating voltage, $\mathbf{V}_{s's}$, which is of variable magnitude and operated within a limited angle. When this compensating voltage is connected in series with the line, the effective sending-end voltage, $\mathbf{V}_{s'}$, is modified. Fig. 9(a) shows that the voltage at any point in the electrical system is applied to a shunt-connected single-core, three-phase transformer's primary windings. A total of six secondary windings (a1 and c2 on the core of A-phase, b1 and a2 on the core of B-phase, and c1 and b2 on the core of C-phase) constitute the impedance-regulating unit. By choosing the number of turns of each of the two windings, the compensating voltage in any phase is derived from the phasor sum of the voltages induced in a two-phase winding set (a1 and a2 for connection in A-phase, b1 and b2 for connection in B-phase, and c1 and c2 for connection in C-phase). Fig. 9(b) shows that the angle, β, of the series-connected compensating voltage, $\mathbf{V}_{s's}$, with respect to the line voltage, $\mathbf{V}_s$, can vary between 0^o and –120^o.

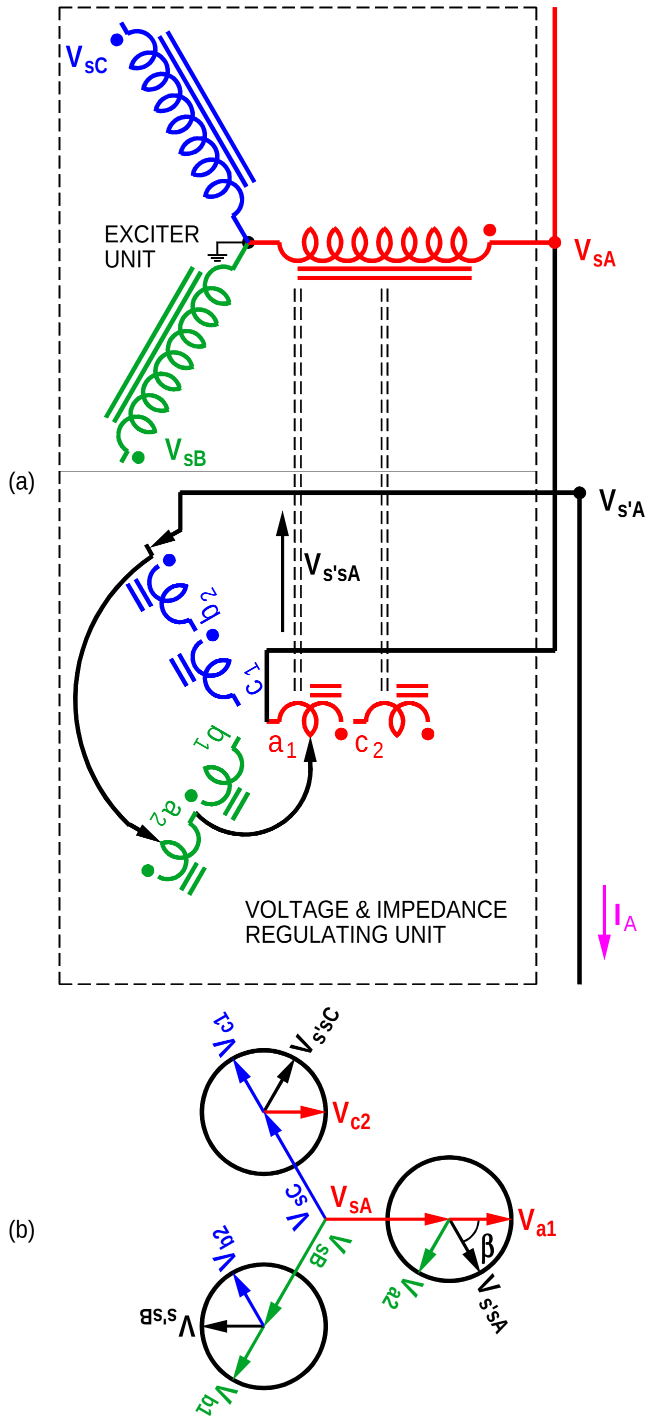

Fig. 9. Impedance regulator operating between 0° and -120°

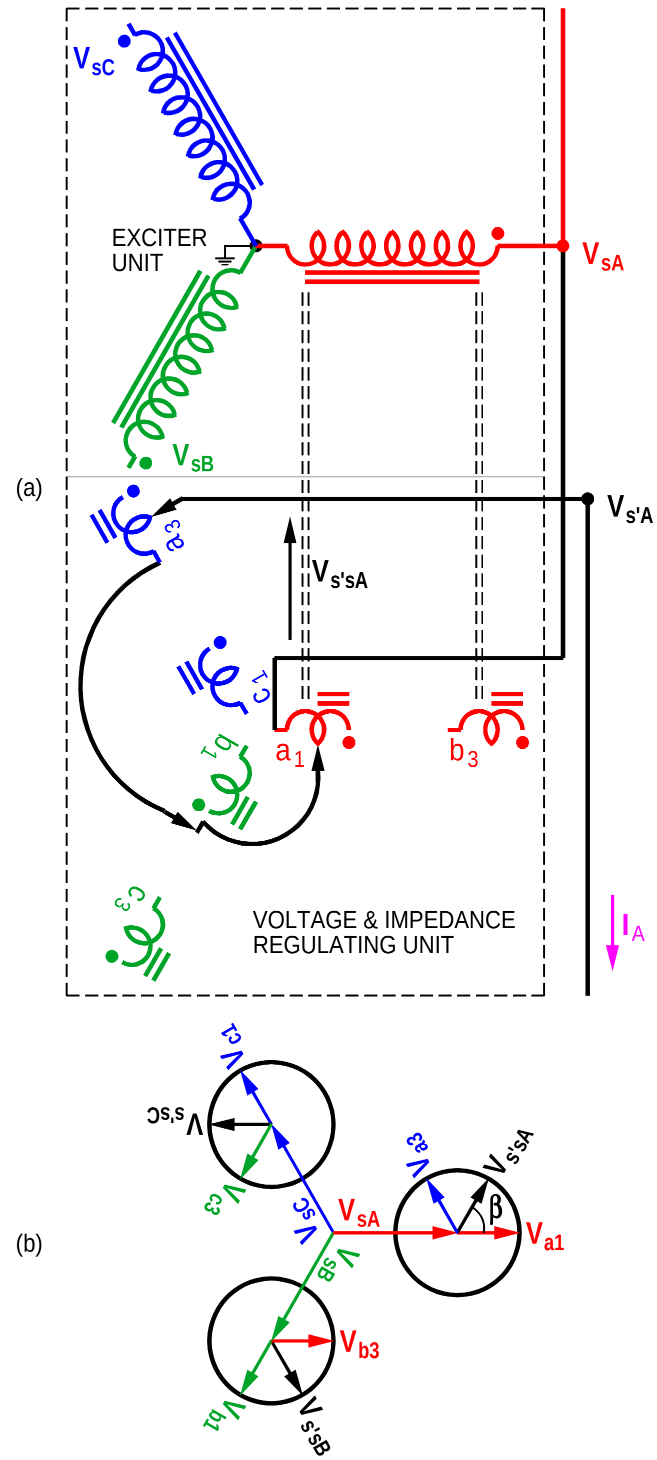

Fig. 10. Impedance regulator operating between 0° and +120°

Similarly, in an application where there is a need to vary the angle, β, of the series-compensating voltage, $\mathbf{V}_{s's}$, between 0 and +120°, an impedance-regulating unit with only 6 windings as shown in Fig. 10(a) are needed. This is achieved by constructing the series-connected voltage from a combination of two voltages [Fig. 10(b)], each of which is induced in a separate winding of a 2-phase set (a1 and a3 for connection in A-phase, b1 and b3 for connection in B-phase, and c1 and c3 for connection in C-phase).

Lastly, in an application where there is a need to vary the angle, β, of the series-compensating voltage, $\mathbf{V}_{s's}$, between +120° and +240°, an impedance-regulating unit with only six windings as shown in Fig. 11(a) is needed. This is achieved by constructing the series-connected voltage from a combination of two voltages [Fig. 11(b)], each of which is induced in a separate winding of a 2-phase set (a2 and a3 for connection in A-phase, b2 and b3 for connection in B-phase, and c2 and c3 for connection in C-phase).

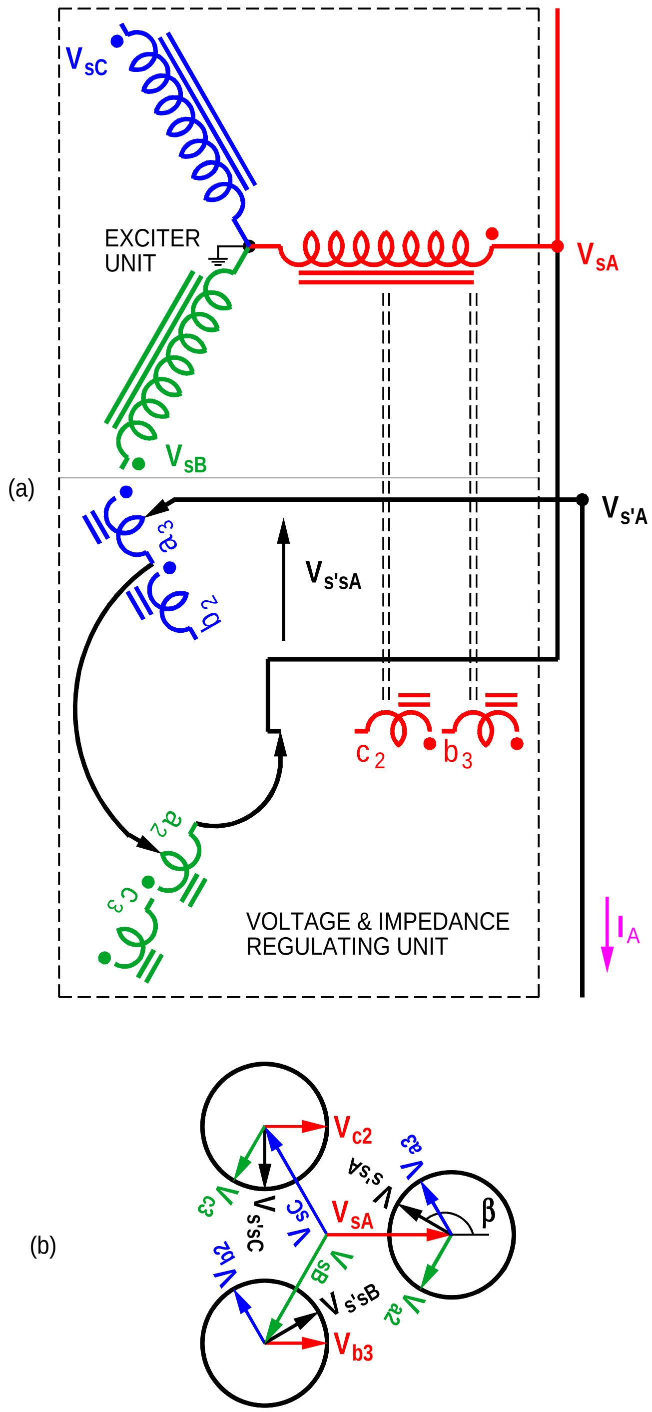

Fig. 11. Impedance regulator operating between +120° and +240°

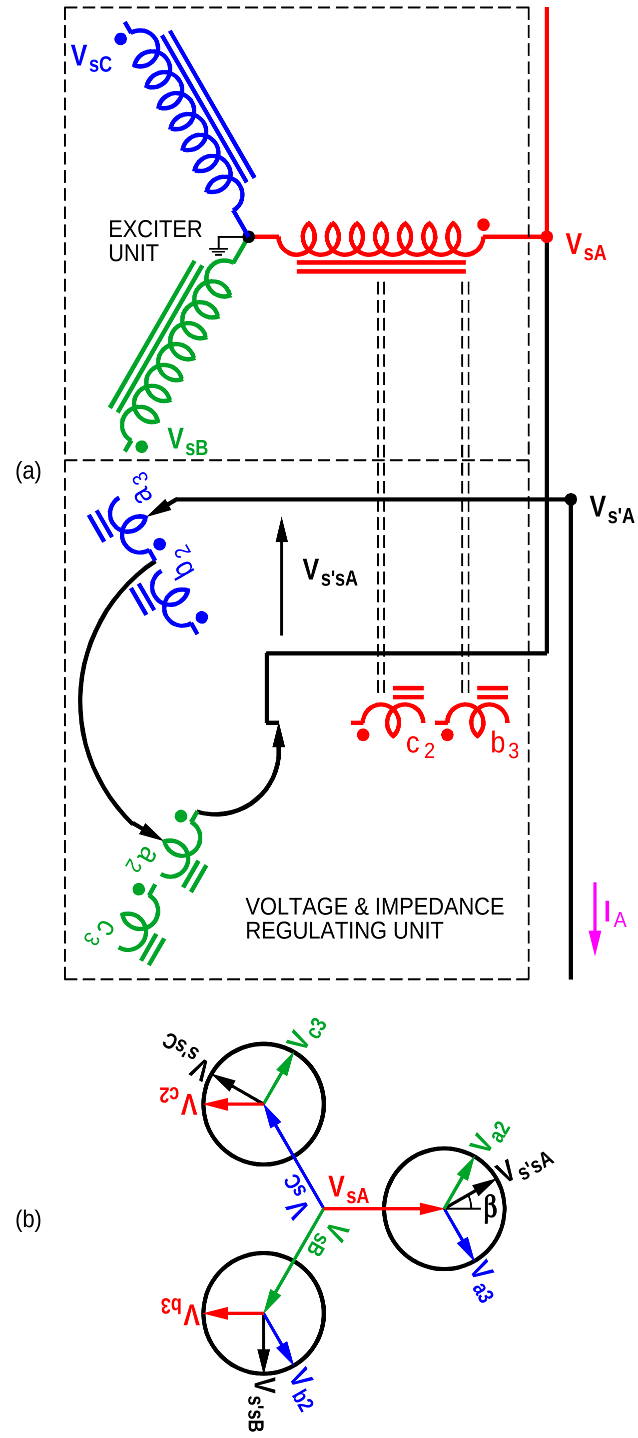

Fig. 12. Impedance regulator operating between -60° and +60°

Extending the concept just presented, if the polarities of the windings in the impedance-regulating unit are reversed, the angle, β, of the series-compensating voltage, $\mathbf{V}_{s's}$, can vary between -60° and 60°. The schematic for this configuration is shown in Fig. 12. In the same way, if the polarities of the windings in the impedance-regulating units, presented in Figs. 9 and 10, are reversed then the angle, β, of the series-compensating voltage, $\mathbf{V}_{s's}$, can vary between 60° and 180° and 180° and 300°, respectively.

In all these cases, the compensating voltage can be at any angle with the prevailing line current, which emulates, in series with the line, a capacitor or an inductor and a positive or a negative resistor. The effect is such that the real and the reactive power flow in a transmission line can be regulated independently. In addition, the function of a voltage regulator can also be implemented provided that the final variable magnitude and variable angle of the compensating voltage are within the controllable operating range.

VI. Conclusion

A new voltage regulator connects a compensating voltage in series with the line either in- or out-of-phase with the line voltage. The effect is such that the voltage at any point in the transmission line is regulated. A new impedance regulator connects a compensating voltage in series with the line and at any angle with the prevailing line current, which emulates, in series with the line, a capacitor that increases the power flow of the line or an inductor that decreases the power flow of the line and a positive resistor that absorbs real power from the line or a negative resistor that delivers real power to the line. The effect is such that the magnitude and the phase angle of the sending-end voltage are modified for independent regulation of the real and the reactive power flow in a transmission line. The functions of voltage regulation and independent control of real and reactive power flow may be combined in just one unit of the "Sen" Transformer family. Any compensator, which provides compensation for one of the transmission line parameters (voltage, angle or reactance) operates on a set of linear operating points inside the *P-Q* circle of a "Sen" Transformer.

The family of "Sen" Transformers connects a series-compensating voltage of variable magnitude at any angle with respect to the line voltage as well as the prevailing line current. The compensating voltage exchanges both real and reactive power with the line. Since the compensating voltage is derived from the line voltage through a transformer action with the primary windings, the exchanged real and reactive power with the line must flow through the primary windings to the line. A series-connected compensating voltage, which is, say, X% of the line voltage, provides a shunt current that is the same X% of the line current. The shunt current through the exciter unit has both real and reactive components. The loading effects of these two currents on the power system network are independent of each other. Therefore, if it is desirable to compensate the combined loading effects of the real and the reactive current through the exciter unit into the power system network, a separate shunt-connected reactance compensator may be considered.

The proposed power flow controller provides the generation of a compensating voltage of line frequency for series connection into the transmission line. The dynamic performance of the proposed power flow controller is limited by the operation of the mechanical tap changer, which is quite adequate for most utility applications. The dynamic performance can be improved, when needed, by replacing the mechanical tap changers with suitable solid-state switches.

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