ISSUE: September 2015

Overview Of Voltage Regulation Schemes For Utility And Industrial Applications

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Electric power sources are frequently located away from population centers. Therefore, the electricity must be transported from the power sources to consumers through transmission and distribution lines. The voltage changes its magnitude and phase angle at any point along a line due to the voltage drop across the line impedance, which is caused by the flow of current in the line. However, the voltage at a point-of-common-coupling with a load must be maintained within the regulatory limits.

Voltage regulation techniques have been practiced in power grid applications with the use of inductors, capacitors, transformers and load tap changers (LTCs) since the earlier days of electrical engineering. However, the latest trend is to use more and more power electronics-based solutions. Even though the costs of the available solutions vary widely, the basic underlying theory of voltage regulation is still the same as it always has been.

The voltage control techniques, described in this article, are applicable in electric transmission lines as well as various other applications, such as motor drives, flicker control, harmonic mitigation, and so on. In examining the various solutions for voltage regulation, this article looks at how these solutions address both functional and cost demands. This article also discusses the evolution of the power electronics inverter-based solution, explaining its interesting capabilities and the challenges it has to overcome to expand its use.

Principles Of Voltage Regulation

An electric power grid is a network of interconnected transmission and distribution lines that carries electrical energy from the generating points (power sources) to the points of use (loads) as shown in Fig. 1. In the process, the line incurs power loss in the resistance of the line. In addition, reactive power is absorbed in the series-connected inductance of the line, while reactive power is generated in the shunt-connected line to ground capacitance.

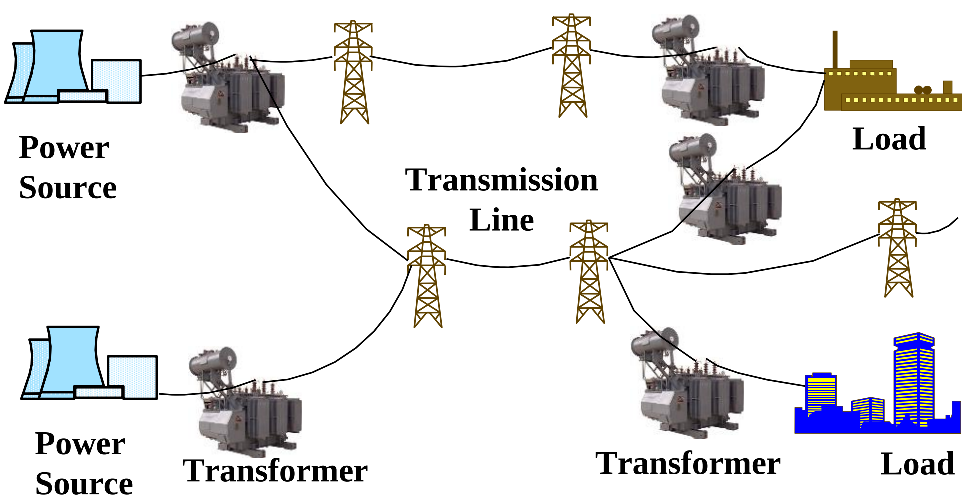

Fig. 1. Part of a large interconnected transmission system supplying electric power from the power sources to the loads.

Let us consider the power system network, shown above, to be represented at the point of compensation by a Thèvenin voltage (V_{TH}) and a Thèvenin impedance (Z_{TH}) as shown in Fig. 2.

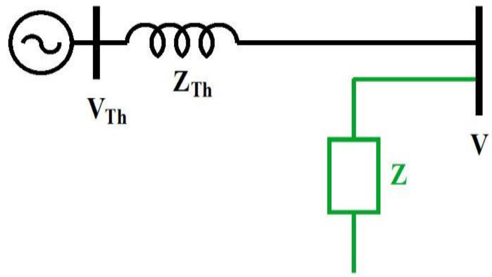

Fig. 2. Equivalent transmission line with shunt compensation.[1]

When a compensating impedance (**Z**) is connected in shunt, the voltage across the compensating impedance is

$$V = \left|\frac{\mathbf{Z}}{\mathbf{Z_{TH}} + \mathbf{Z}}\right| V_{TH} \; . \qquad (1)$$

If Z_{TH} is represented by a reactance (jX_{Line}), equation 1 becomes

$$V = \frac{1}{\left|1 + \frac{jX_{Line}}{\mathbf{Z}}\right|} V_{TH} \; . \qquad (2)$$

The compensating impedance (Z) can be resistive (R), inductive ($jX_L = j\omega L$), or capacitive ($-jX_C = 1/j\omega C$).

For the case where Z = R, the voltage across the compensating impedance becomes

$$V = \frac{1}{\left|1 + \frac{jX_{Line}}{R}\right|} V_{TH} = \frac{1}{\sqrt{1 + \left(\frac{X_{Line}}{R}\right)^2}} V_{TH} \; . \qquad (3)$$

The denominator of this equation is always greater than 1, hence $V < V_{TH}$. Therefore, adding a shunt resistor results in lowering the line voltage, which is a side-effect of connecting a load to the grid. Next, the effects of a shunt-connected inductor and capacitor are examined.

For the case where Z = jX_L, the voltage across the compensating impedance becomes

$$V = \frac{1}{\left|1 + \frac{jX_{Line}}{jX_L}\right|} V_{TH} = \frac{1}{1 + \frac{X_{Line}}{X_L}} V_{TH} \; . \qquad (4)$$

The denominator of this equation is always greater than 1, hence $V < V_{TH}$. Therefore, adding a shunt inductor also results in lowering the line voltage.

For the case where Z = $-jX_C$, the voltage across the compensating impedance becomes

$$V = \frac{1}{\left|1 + \frac{jX_{Line}}{-jX_C}\right|} V_{TH} = \frac{1}{1 - \frac{X_{Line}}{X_C}} V_{TH} \; . \qquad (5)$$

The denominator of this equation is always less than 1, hence $V > V_{TH}$. Therefore, adding a shunt capacitor results in increasing the line voltage.

Sometimes it is desirable to decrease the line voltage. In a lightly-loaded line, the reactive power absorbed by the line's inductance becomes much less in comparison to the reactive power generated by the line's capacitance. The resulting increase of voltage in the line may reach or exceed the allowable limits for other system equipment. Sometimes it is the opposite when an increase in the voltage of the line is highly desirable.

In a heavily-loaded transmission line, the reactive power needed by the line's inductance becomes much more in comparison to the reactive power generated by the line's capacitance. The resulting voltage along the line may decrease to a level, which is below an acceptable limit that may cause brown-out or even voltage collapse, leading to power system instability. Therefore, the voltage level along the transmission line must be regulated to its nominal value as explained next.

A simple power transmission system with a sending-end voltage, V_s (i.e., $V_s \angle\delta$), and a receiving-end voltage, V_r (i.e., $V_r \angle 0$), connected by the line's reactance (X), and the related phasor diagrams are shown in Fig. 3. The voltage, V_X (i.e., $V_s - V_r$), across the line's reactance (X) is the difference between the sending- and receiving-end voltages. The resulting current (I) in the line lags the voltage (V_X) by 90°. The active and reactive power flows at the sending end are P_s and Q_s, and at the receiving end are P_r and Q_r, respectively, which are defined by the following equations.

$$P_s = P_r = \frac{V_s V_r}{X}\sin\delta \quad (6)$$

$$Q_s = \frac{V_s V_r}{X}\left\{\frac{V_s}{V_r} - \cos\delta\right\} \quad \text{and} \quad Q_r = \frac{V_s V_r}{X}\left\{\cos\delta - \frac{V_r}{V_s}\right\} \quad (7a, b)$$

The magnitude and phase angle of the voltage with respect to the line current are different at every point along the transmission line. The intermediate line voltages (i.e., V_1, V_2, etc.) are smaller in magnitude than the sending- and receiving-end voltages (V_s and V_r). The smallest voltage (V_m) is at the midpoint of the transmission line in this illustration (Fig. 3, again.)

The direct or active and quadrature or reactive components of the line current at the sending end are I_{ds} and I_{qs} and the same at the receiving end are I_{dr} and I_{qr}. Since the current is lagging at the sending end, the sending-end voltage supplies reactive power to the reactance of the left half of the line. Since the current is leading at the receiving end, the receiving-end voltage supplies reactive power to the reactance of the right half of the line. The midpoint of the line operates at unity power factor.

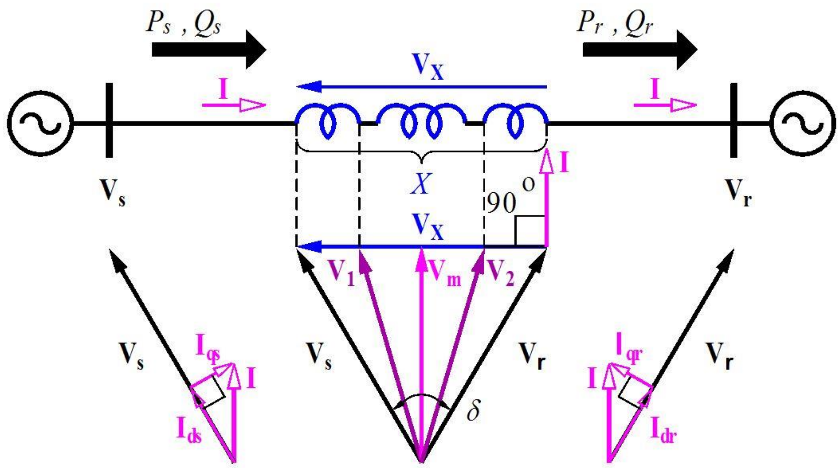

Fig. 3. A simple power transmission system and the related phasor diagrams. [1]

Increasing the voltage along the line at various points increases the available transfer capacity (ATC) of the line. This is significant for lines that operate with a large power angle (δ). Considering $V_s = V_r = 1$ pu (per unit) and $X = 1$ pu, if V_m is raised to be 1 pu, the ATC changes from sinδ to 2*sin(δ/2). For a δ = 30°, that is a 3.53% increase of active power flow. In an extreme case, δ = 90° would result in an increase of 41.4% in active power flow.

The capacitive compensation unit at the midpoint of the line supplies reactive power to the reactance of the second quarter of the line as well as the third quarter of the line. In this case, the sending- and the receiving-end voltages supply reactive power to the first quarter and the fourth quarter of the line, respectively. Note that if a line is compensated at ¼, ½ and ¾ points to maintain the nominal voltage, the ATC changes from sinδ to 4*sin(δ/4). For a δ = 90°, that is a 53% increase in active power flow.

The increased voltage due to voltage compensation in the line increases the active power flow over the natural flow when no compensation is applied. This results in higher line utilization, meets greater customer needs, integrates new sources of energy, and avoids building of new transmission lines, at least for now.

The available solutions for voltage compensation range from using transformer and LTCs to power electronics, which can be divided into two categories: naturally-commutated switch-based solutions and forced-commutated switch-based solutions. Each of these solutions is based on engineering tradeoffs. In particular, as the response speed of the solution increases from slow (seconds) to medium speed (cycles) to fast (milliseconds), there is a corresponding increase in the solution's cost (installation and maintenance), complexity and non-portability.

Other important features to consider are reliability, efficiency and component non-obsolescence. The objective of this article is to present how various solutions for voltage regulation can be used in utility and industrial applications to meet both functional and cost requirements.

Various Solutions For Voltage Regulation

For more than a century, the transmission line voltage has been regulated with a transformer and LTCs—this combination is referred to as a voltage regulating transformer (VRT) as shown in Fig. 4. An LTC can step up or step down the voltage without interruption of the load current. In this method, a compensating voltage is added vectorially in- or out-of-phase with the voltage of the transmission line at the point of connection.

Note that a transformer neither generates nor absorbs var. If a transformer delivers var at one side (primary or secondary), it absorbs the same on the other side (secondary or primary). Therefore, in the process of increasing voltage on the secondary side, it reduces voltage on the primary side. The opposite is true as well when, in the process of decreasing voltage on the secondary side, it increases voltage on the primary side as shown in Fig. 5.[1] In this example, the system data given in Table 1 are used.

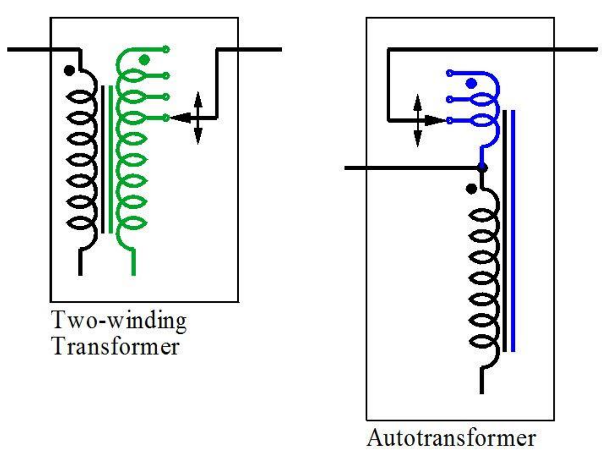

Fig. 4. Voltage regulating transformers.[1]

Table 1. Electrical systems data.[1]

Parameters	Values
Base values	160 MVA and 138 kV
Sending-end line-to-line voltage	$1\angle 0°$ pu
Receiving-end line-to-line voltage	$1\angle -20°$ pu
Series impedance for sending-end source	6.25% = 1.0053 Ω and 19.73 mH
Series impedance for receiving-end source	0 Ω and 0 mH
Transmission line impedance	18.75% = 3.0159 Ω and 59.19 mH

Fig. 5 shows that a compensating voltage of ±15% of the natural primary voltage (V_{sn}) of 0.99 pu results in a secondary voltage ($V_{s'}$) in the range of 0.87 to 1.09 pu. In the process, the primary voltage (V_s) varies in the range of 1.02 to 0.95 pu.

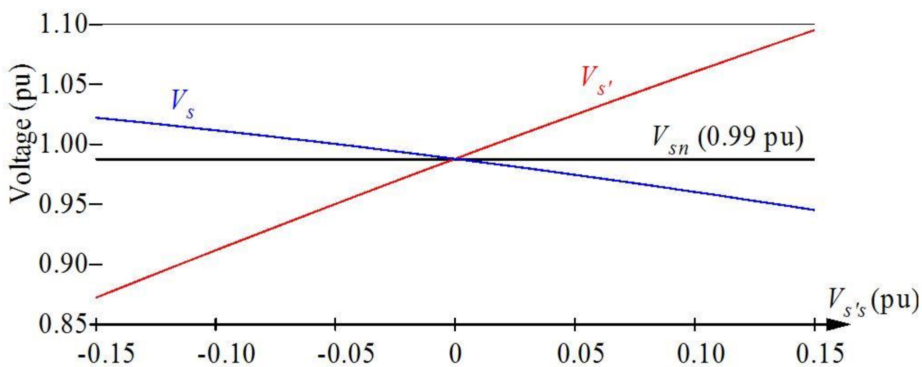

Fig. 5. Ranges of voltages (V_s and $V_{s'}$) at the primary and secondary sides of voltage regulating transformers.[1]

The true method of regulating the line voltage is to connect an inductor or a capacitor in shunt with the line as shown in Fig. 6. A shunt-connected inductor absorbs reactive power from the line and lowers the line voltage, whereas a shunt-connected capacitor raises the line voltage with its generated reactive power.

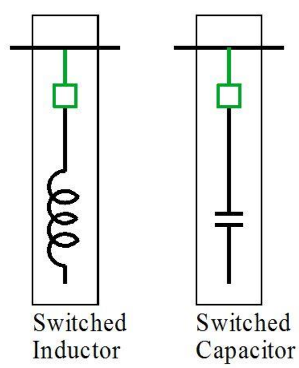

Fig. 6. Shunt-connected switched inductor/capacitor.

Fig. 7 shows a sample case in which the shunt-connected capacitor is chosen to draw one pu of reactive current from the line at the point of compensation. The resulting line voltage is 1.035 pu. During the connection of the shunt capacitor to the grid, it might cause unacceptable levels of voltage and current transients.

The figure shows the digital simulation results from connecting a three-phase shunt capacitor bank to the transmission line. Between 0 and 50 ms, the shunt breaker (SNHBRK) stays open and the natural voltage at the point of compensation is 0.99 pu. At 50 ms, the SNHBRK closes and the shunt capacitor is connected to the line. The inrush current (i_{1a}) of phase *a* exceeds four pu. The instantaneous voltage of phase *a* exceeds 0.75 pu over the nominal value.

Under steady-state conditions, the current (i_{1a}) of phase *a* through the shunt capacitor leads the line voltage (v_{1a}) of phase *a* by 90° with a magnitude of one pu. The line voltage becomes 1.03 pu at the point of compensation. Therefore, the compensating reactive power becomes -1.03 pu (capacitive). At 250 ms, the SNHBRK opens to disconnect the shunt capacitor from the line, the current through the shunt capacitor reduces to zero, and the line voltage at the point of compensation becomes the original 0.99 pu. When the capacitor disconnects, a spike in voltage occurs at the point of compensation due to the sudden change in flow of current through the line inductance.

Just prior to closing the switch, the voltage on one side of the contact of the shunt breaker (SHNBRK) is the capacitor voltage, which is zero. On the other side of the contact is the line voltage and it is different instantaneously on three different phases. The worst-case inrush current will occur in any phase if the contact closes on a peak voltage. The most desirable scenario is if the contact closes on zero voltage.

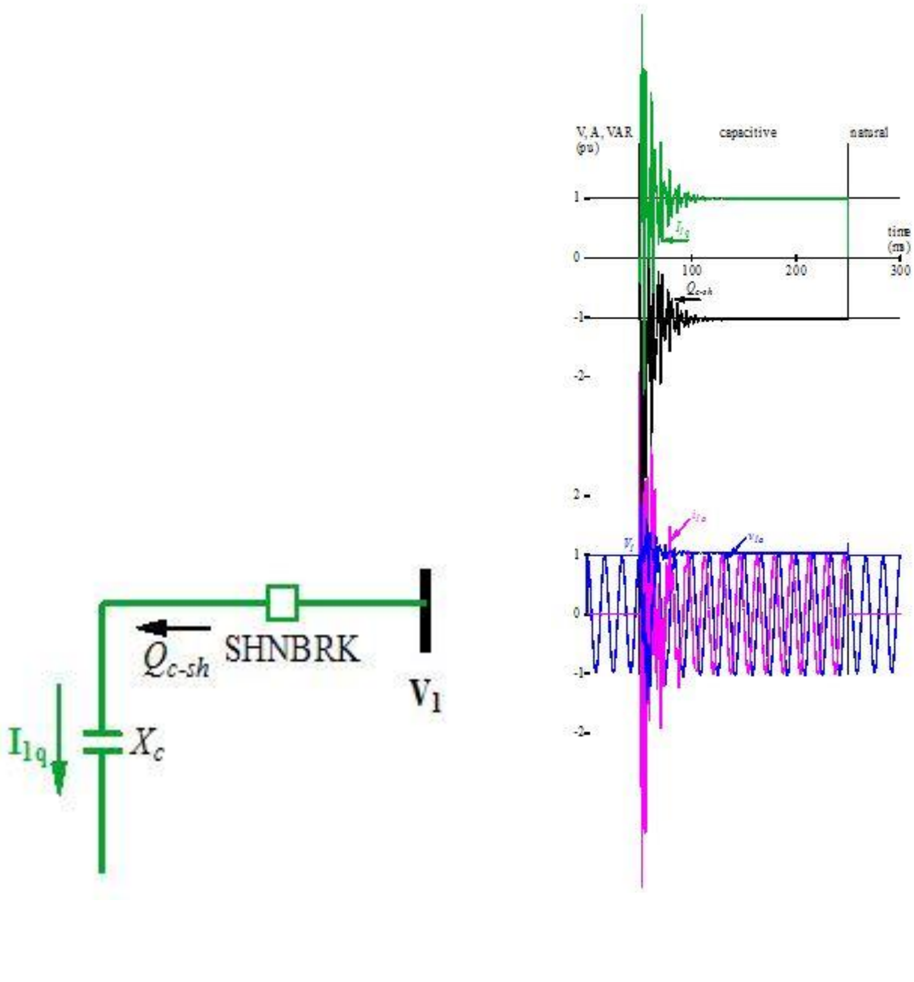

Fig. 7. Shunt-connected mechanically switched capacitor (schematic on left); exchanged reactive power and the resulting voltages and currents (waveforms on right).[1]

The inrush current through the capacitor can be limited by connecting the shunt capacitor through a series reactor as shown in Fig. 8. After the initial transients die out, the series reactor is shorted out by closing a bypass breaker (BYPBRK) and leaving only the shunt capacitor in the circuit. The bypass reactor (Xbyp) is chosen to be 20% of the compensating reactance (Xc) with a quality factor (Q) of 10.

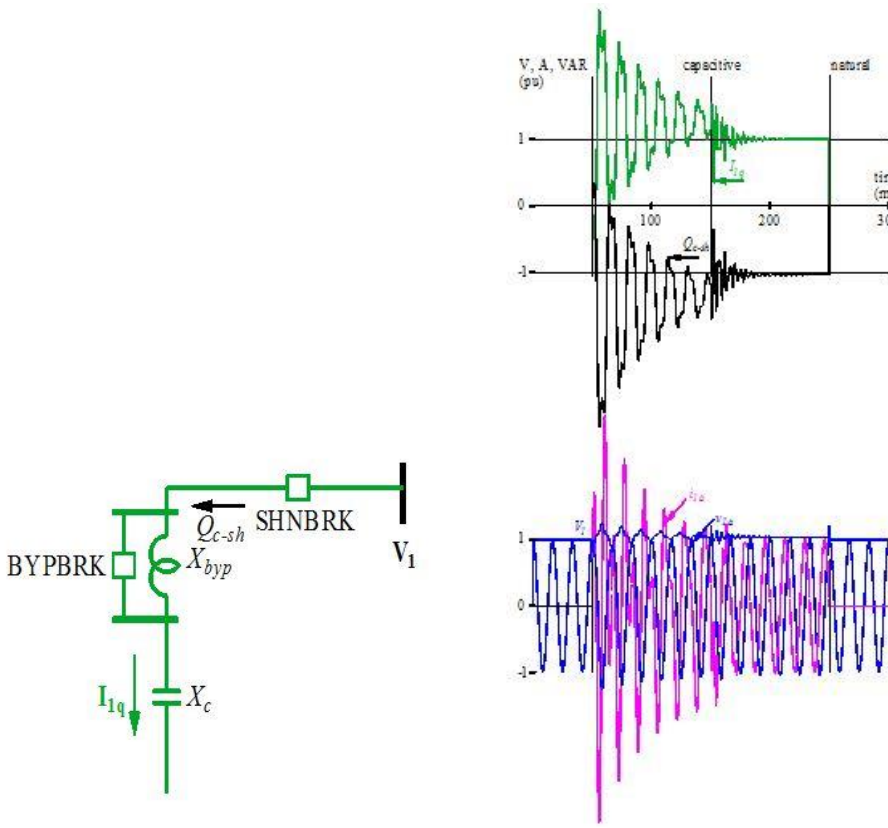

Fig. 8. Shunt-connected mechanically switched capacitor (schematic on left); exchanged reactive power and the resulting voltages and currents (waveforms on right).[1]

The figure shows the digital simulation results when a three-phase shunt capacitor bank is connected to the transmission line through three-phase series reactors that are bypassed after a certain time. Between 0 and 50 ms, the shunt breaker (SNHBRK) stays open and the natural voltage at the point of compensation is 0.99 pu. At 50 ms, the SNHBRK closes and the shunt capacitor with the series reactor is connected to the line. The inrush current (i_{1a}) of phase *a* barely exceeds 3.2 pu. The instantaneous voltage (v_{1a}) of phase *a* reaches 0.18 pu over the nominal value.

At 150 ms, the BYPBRK closes to short out the series reactor, causing some transients to occur in the currents and voltages. After the transients die out, the current (i_{1a}) of phase *a* through the shunt capacitor leads the line voltage (v_{1a}) of phase *a* by 90° with a magnitude of one pu. From this point onward, the circuit operation is the same as before.

Another approach is to use shunt inductors or capacitors through thyristor switches, which are power electronics-based naturally-commutated switches that can be turned on during the positive half cycle of an ac voltage, but turn off naturally when the voltage reverses. During the evolution of this approach over the last five decades, the various electronic topologies and their control methods became known as the thyristor-switched capacitor (TSC), thyristor-switched reactor (TSR), and thyristor-controlled reactor (TCR).

The TSC connects fixed capacitors in a step-like manner in shunt with the line. The TSR connects fixed inductors in a step-like manner in shunt with the line. (Note that the TSR is rarely used.) The TCR connects an inductor in shunt with the line through thyristor switches whose duty cycle can be varied, thereby making it appear like a variable inductor. A combination of TSC, TSR, and TCR is termed the static var compensator (SVC), as shown in

Fig. 9. A capacitor with a parallel inductor offers a compensating reactance of

$$X_c = \frac{X_L X_C}{j(X_L - X_C)} = j\frac{X_L X_C}{(X_C - X_L)}. \qquad (8)$$

When $X_C > X_L$, X_c is inductive and when $X_C < X_L$, X_c is capacitive. Fig. 10 shows the voltage profile without SVC (left) and with SVC (right).

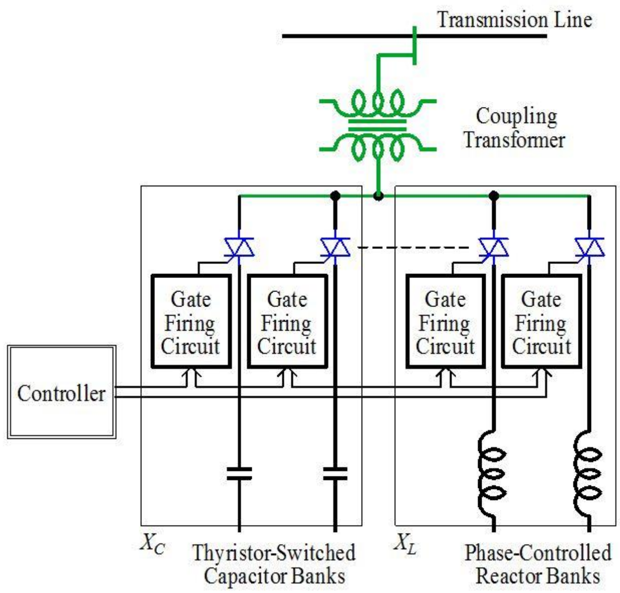

Fig. 9. Static Var Compensator (SVC).[2]

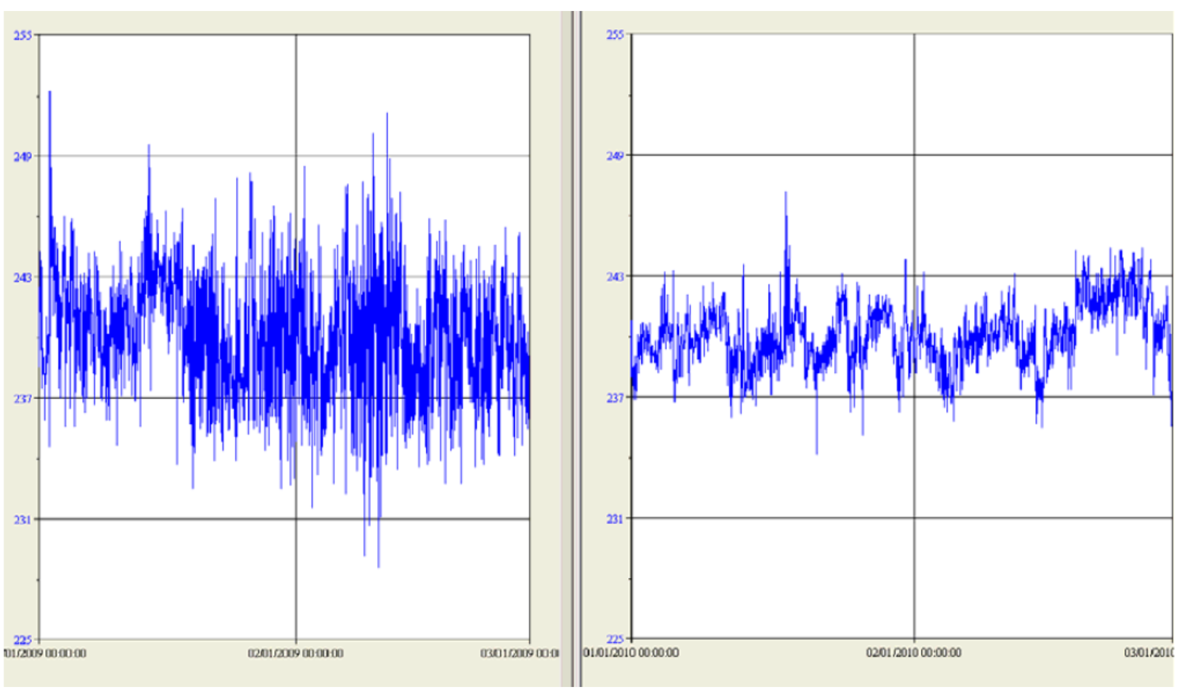

Fig. 10. Voltage profile without SVC (left) and with SVC (right).[3]

Another method that has been used for over 100 years is the use of a synchronous machine to draw inductive or capacitive current and, thereby, regulate the voltage at the point-of-common coupling. A simple two-bus power system network model is shown in the single line diagram of Fig. 11.

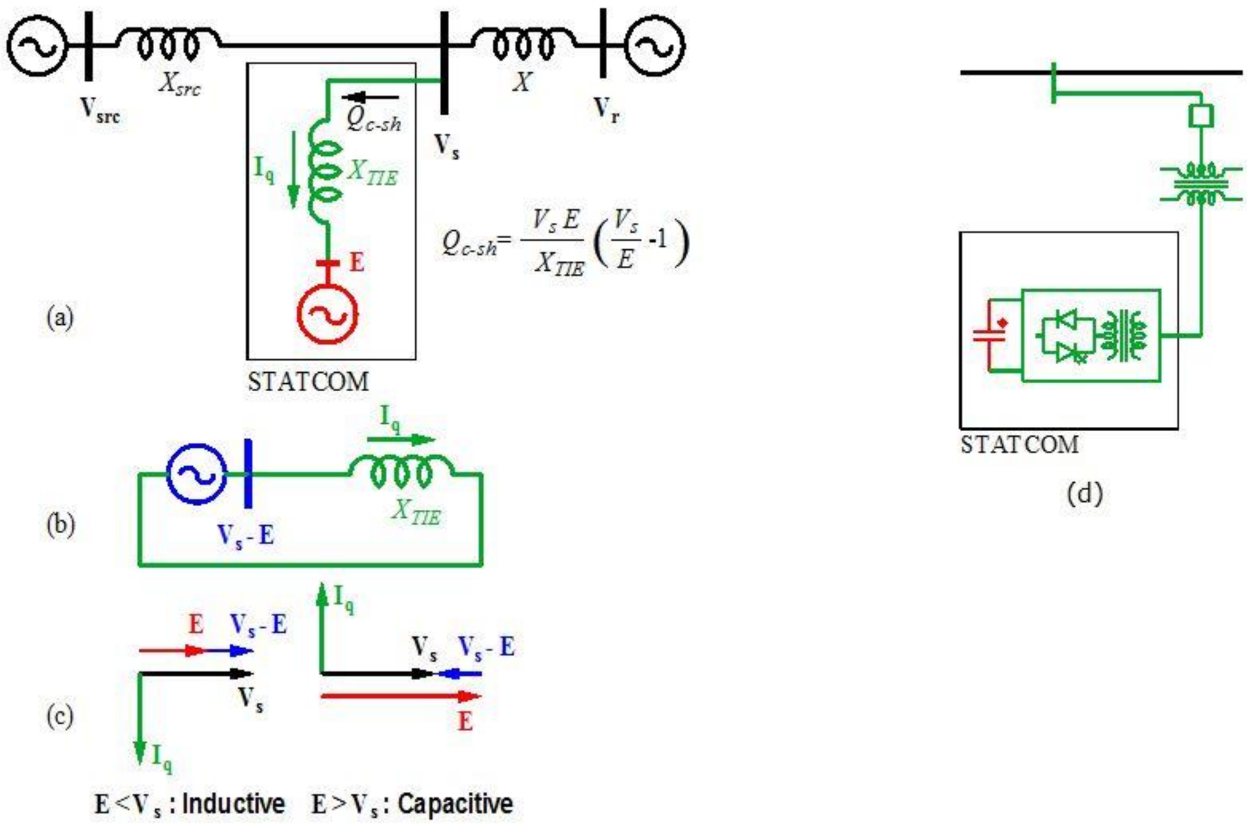

Fig. 11. Concept of STATic synchronous COMpensator (STATCOM) (a), equivalent circuit (b), phasor diagram (c) and realization of STATCOM (d).[1]

The network is driven by a source voltage (V_{src}) behind a source reactance (X_{src}). The transmission line reactance is X and the sending- and receiving-end voltages are V_s and V_r. The indirect way to implement a variable shunt capacitor or a variable shunt inductor is to generate a variable magnitude compensating voltage (E) in phase with the line voltage (V_s) at the point of compensation and to connect the compensating voltage in shunt with the line through a tie reactance (X_{TIE}).

If the transmission line voltage (V_s), compensating voltage (E), and tie reactance (X_{TIE}) are thought of as the sending-end voltage, receiving-end voltage, and line reactance, respectively, then the active power absorbed (which is proportional to $\sin\delta$) from the transmission line at the point of compensation is zero because the transmission line voltage and the compensating voltage are in phase ($\delta = 0°$). However, the compensating reactive power absorbed from the line is

$$Q_{c-sh} = \frac{V_s E}{X_{TIE}}\left(\frac{V_s}{E} - 1\right). \quad (9)$$

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), which is an inverter consisting of power electronics-based forced-commutated switches that can be turned on and off as desired, a variable magnitude shunt-connected voltage source is implemented.[1]

A variable magnitude, shunt-connected compensating voltage is implemented with the use of the STATCOM as shown in Fig. 11a, which is realized as an inverter and a coupling transformer as shown in Fig. 11d. A net voltage (V_s-E) drives a current (I_q) through the tie reactance (X_{TIE}) as shown in Fig. 11b. The current (I_q) always lags the driving voltage (V_s-E) by 90°. Through control action, the magnitude of the compensating voltage (E) can be made higher or lower than the line voltage (V_s).

When $E < V_s$ as shown in Fig. 11c, the current (I_q) through the STATCOM lags the terminal voltage (V_s) and the line "sees" an inductive reactance connected at its terminal. The STATCOM is considered to be operating in an inductive mode and reactive power is absorbed at the point of compensation by the emulated inductor. Similarly, when $E > V_s$ as shown in Fig. 11c, the current (I_q) through the STATCOM leads the terminal voltage (V_s) and the line "sees" the STATCOM as a capacitive reactance. The STATCOM is considered to be operating in a capacitive mode and reactive power is delivered at the point of compensation by the emulated capacitor.

The concept of connecting a variable amplitude synchronous ac voltage in shunt with the ac line through inductive impedance has been practiced since the introduction of the synchronous condenser in which the internal voltage (E) of the synchronous machine is controlled by controlling the field current. The differences between an inverter-based STATCOM and a rotating machine-based synchronous condenser are that (1) there are no wear and tear of moving parts in a STATCOM and (2) the response time is a few milliseconds whereas the exciter time constant of a 100-Mvar rated machine is measured in seconds.

In 1985, Westinghouse installed a ±1-MVA-rated power electronics inverter-based shunt reactance emulator and demonstrated its operation for the first time at EESERCO.[4] In the most general form, this type of controller can be programmed to operate as a shunt impedance emulator with either an energy transfer capability, such as in back-to-back STATCOM or an energy storage capability on the dc side of the inverter. However, in a special case, it can be programmed to operate as a shunt reactance emulator as well.

Since the early 1990s, the interest in STATCOM has increased significantly due to the availability of high-power semiconductor switches such as 4500-V, 4000-A rated gate-turn-off (GTO) thyristors. In 1995, Westinghouse installed a ±100-MVA-rated STATCOM at the Tennessee Valley Authority's (TVA) Sullivan substation in the state of Tennessee, U.S.A. This was the world's first commercial installation of STATCOM, although this project is discussed in literature as STATCON (static condenser.)

This STATCOM was retired from service after less than two decades of operation. The first commercial STATCOM at TVA demonstrated its fast speed of operation as shown in Fig. 12. Power electronics solutions provide a 100-Mvar step change in 2 ms, which is not required in most utility applications. Fig. 13 shows the voltage regulation at American Electric Power's (AEP) Inez substation using a STATCOM. The response time used at this installation is in seconds.

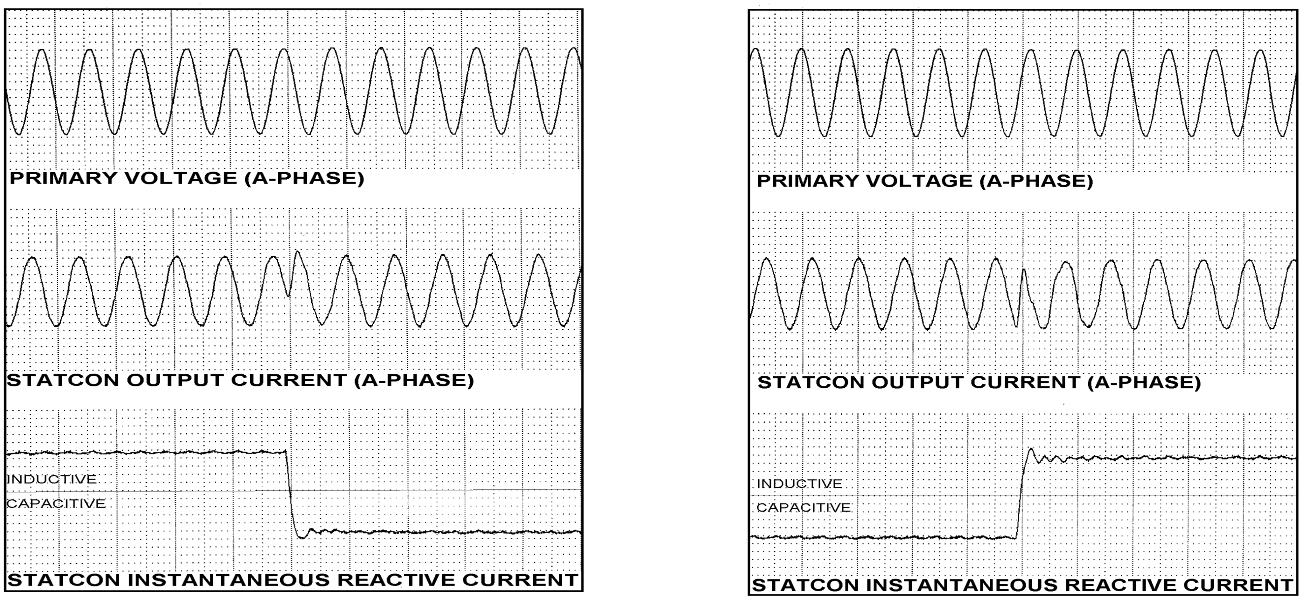

Fig. 12. Operation of STATCOM at TVA.[5]

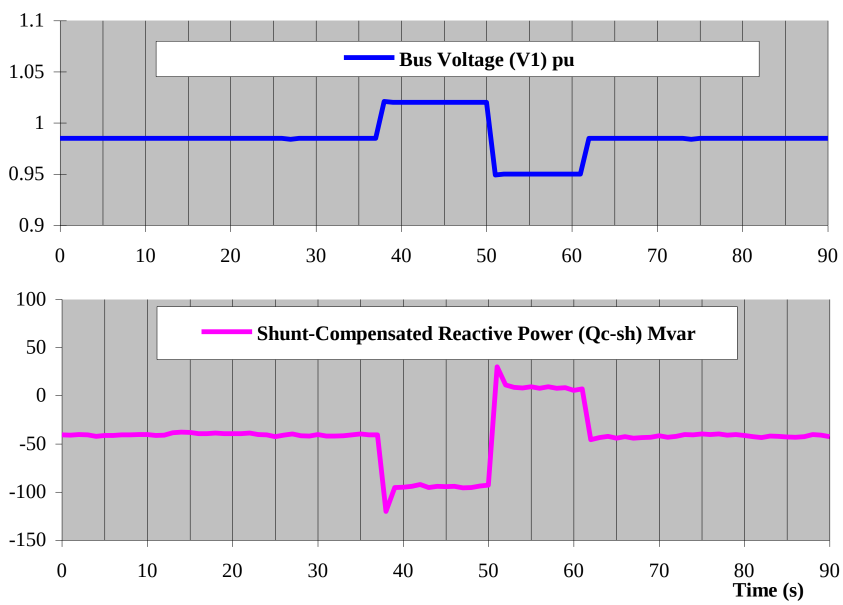

Fig. 13. Operation of STATCOM at AEP.[6]

In the last two decades, a great deal has been learned about the true needs of a utility for its everyday use and they are (a) high reliability, (b) low installation and operating costs, (c) component non-obsolescence, and (d) portability for easy relocation to adapt to a changing power system's needs. The inverter-based STATCOM is capable of providing responses in the range of milliseconds as shown in Fig. 12. However, experience has shown that the response time needed in most utility applications is seconds rather than milliseconds as shown in Fig. 13. In other words, the fast response cannot be utilized in order to assure continued operation under contingencies (i.e. all the possible variations in the number of lines connected as a network at different times.)

However, there are applications where a fast response from a compensator may be what is needed. One such application is shown in Fig. 14 where a Thèvenin voltage source, V_{Th}, is supplying power to a plant through a Thèvenin impedance, Z_{Th}. The input voltage, V, to the plant is stepped down twice through, first, the main transformer and through the furnace transformer. The load is an electric arc furnace.

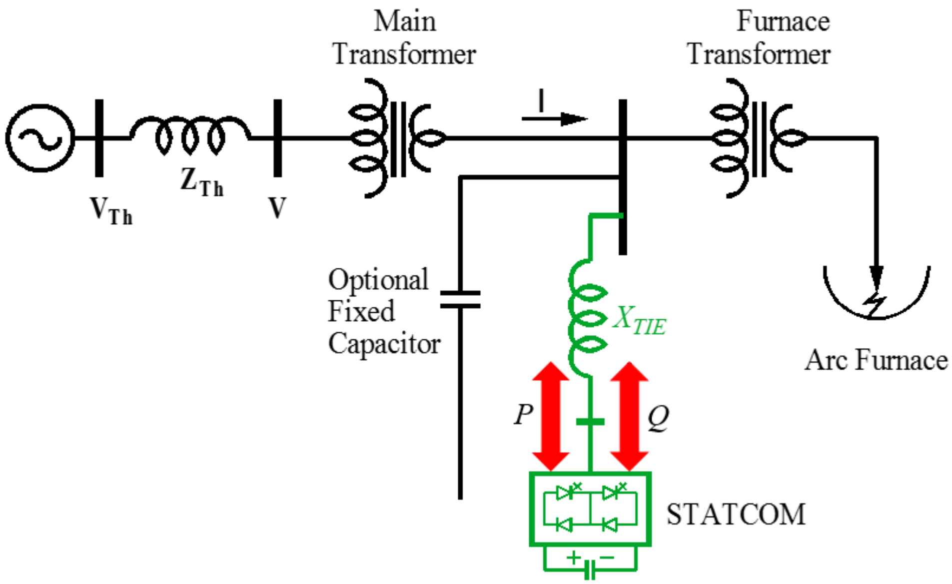

Fig. 14. Use of a STATCOM and a fixed capacitor as an arc furnace compensator.

The random nature of the load creates a random voltage drop across Z_{Th} and, thus, creates a voltage flicker at the input bus to the plant. The fast acting STATCOM provides a unique solution to reduce this voltage flicker by supplying the fluctuating active power and reactive power needs of the load. A typical voltage (V) and current (I) drawn by an electric arc furnace in three phases (A, B and C) are shown in Fig. 15.

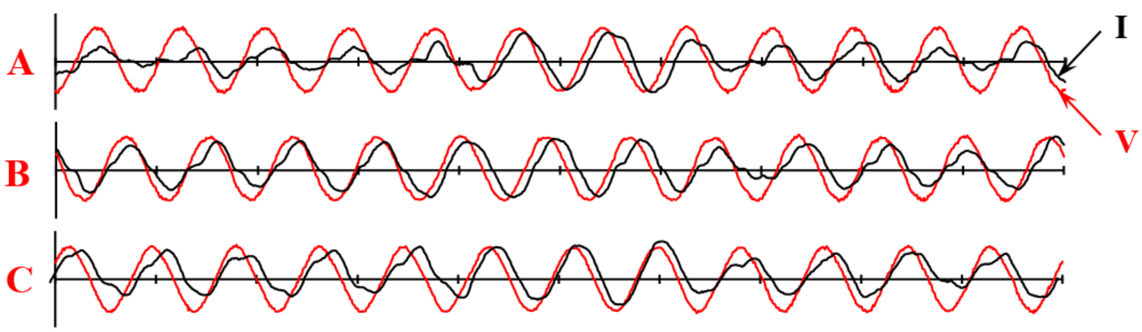

Fig. 15. Terminal voltage (V) and current (I) drawn by a typical electric arc furnace.

The STATCOM and an optional fixed capacitor supply nearly all instantaneous reactive power drawn by the furnace as shown in Fig. 16. The STATCOM also supplies the fluctuating component of the active power, drawn by the furnace, as shown in Fig. 17.

In 1998, Westinghouse installed a ±80-MVA-rated power electronics inverter-based shunt impedance emulator at CMC Steel (then SMI) in Seguin, Texas. This solution uses a larger-than-usual-sized dc capacitor, needed for a utility application, which provides a sink and source of fluctuating active power for the load, thereby leveling off the active power drawn from the utility source. A comparison of voltage flicker (red trace) without and with compensation provided by a STATCOM is shown in Fig. 18.

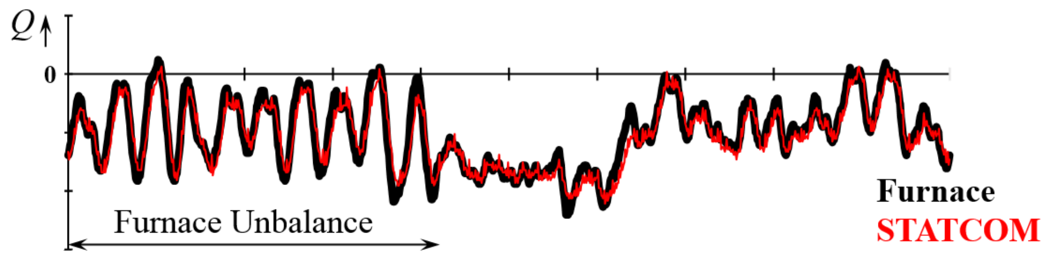

Fig. 16. Reactive power drawn by a furnace and supplied by a STATCOM.

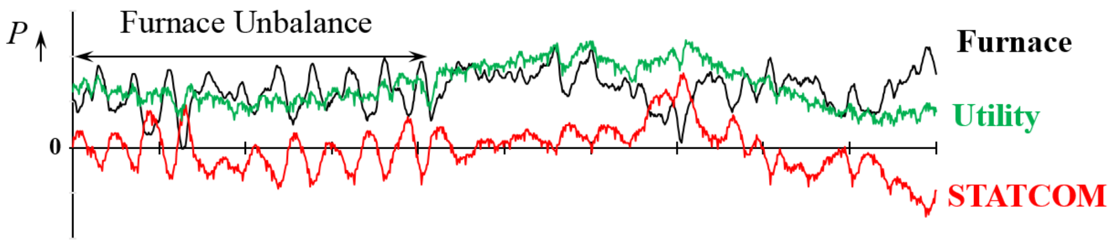

Fig. 17. Active power exchanged by a STATCOM, drawn by a furnace and supplied by a utility.

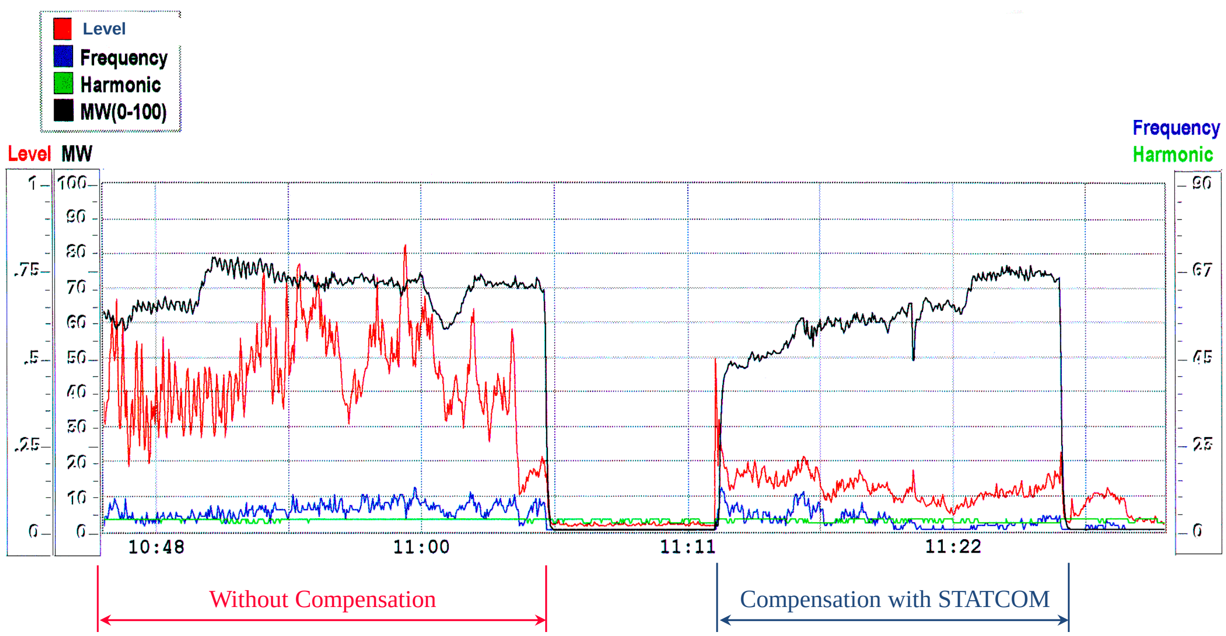

Fig. 18. Flicker measurements without and with a compensation provided by a STATCOM.

The first generation of FACTS controllers consisted of inverters with GTOs, which are forced-commutated semiconductor switches. Since the commissioning of the world's first commercial STATCOM at TVA in 1995, nine GTO inverter-based FACTS controllers were built. During the same time, several IGBT inverter-based FACTS controllers were also built.

During the past two decades, the IGBT technology has advanced by several generations. So, what about the GTO technology? Unfortunately, it is not manufactured anymore. Even though the IGBT is the work-horse in the industry at the present time, the future trend is to develop wide bandgap-type SiC and GaN switches for many reasons—higher-temperature operation, lower loss, smaller snubber circuit, and so on. So how will the GTO inverter-based FACTS controllers get spare parts?

That is not an easy question to answer. Several of the installations with GTO inverters are already dismantled. No one had predicted this day was coming so soon. What is interesting is that the power electronics inverter-based FACTS controllers are still being promoted with the same dubious claims as when they were first introduced two decades ago. Proponents of these controllers are still asserting that they will last for 50 or more years despite the lack of any evidence to support this claim.

In this context, one might ask why not use the latest high-power electronics switches to replace the aging outdated switches? The answer is simple—it is not possible. Even though there is no available switch, which can be considered as a perfect switch, meaning zero forward voltage drop during conduction and zero transition time from on-to-off and vice versa, the snubber circuit, gate-drive circuit and cooling requirements vary for an inverter, made with one type of switch to another. This fact alone forces us to discard the aging inverters when spare parts are not available.

Moreover, the control suite becomes completely outdated in a decade or so, requiring an upgrade. There is no initiative to keep any commercially used, legacy power electronics system alive after it passes its natural longevity. These facts need to be taken into account to calculate the true cost of power electronics inverter-based FACTS controllers.

Even with the above-mentioned challenges about the power electronics inverter-based solutions, there are applications where these are just the right solutions. One such application is the dynamic voltage restorer (DVR). The purpose of a DVR, as its name suggests, is to restore the voltage of a critical load if a sag or swell occurs on a phase-by-phase basis. IEEE Std 1100-1992 (Emerald Book) defines a sag as “An rms reduction in the ac voltage, at the power frequency, for durations from a half-cycle to a few seconds.” Note that the equivalent terminology from the IEC is “dip.”

Fig. 19 shows a single line diagram of a DVR that feeds a critical load, which is located on a power distribution line that is one of several lines supplied by a transmission line through a stepdown transformer. The heart of a DVR is a dc-ac converter (inverter), which is normally bypassed with a thyristor-bypass switch. The dc capacitor is trickle-charged through a stepdown transformer, rectifier and dc-dc converter.

During a voltage sag or swell due to a fault or lightning on an adjacent distribution line, the bypass switch opens and a voltage that is generated by the inverter is placed in series with the load through a coupling transformer to restore the load’s nominal voltage while the conventional system protection equipment clears the fault.

Since a DVR is installed ahead of a sensitive load, it senses the sagged or swelled voltage on its input terminals. The DVR control system is such that it continually compares the incoming voltage waveform with an internal reference voltage signal and determines the proper voltage that must be added or subtracted to restore the nominal voltage at the load terminals. Fig. 20 shows a sag correction by a DVR during a field test. The sag occurred in one phase, which was corrected within a few milliseconds.

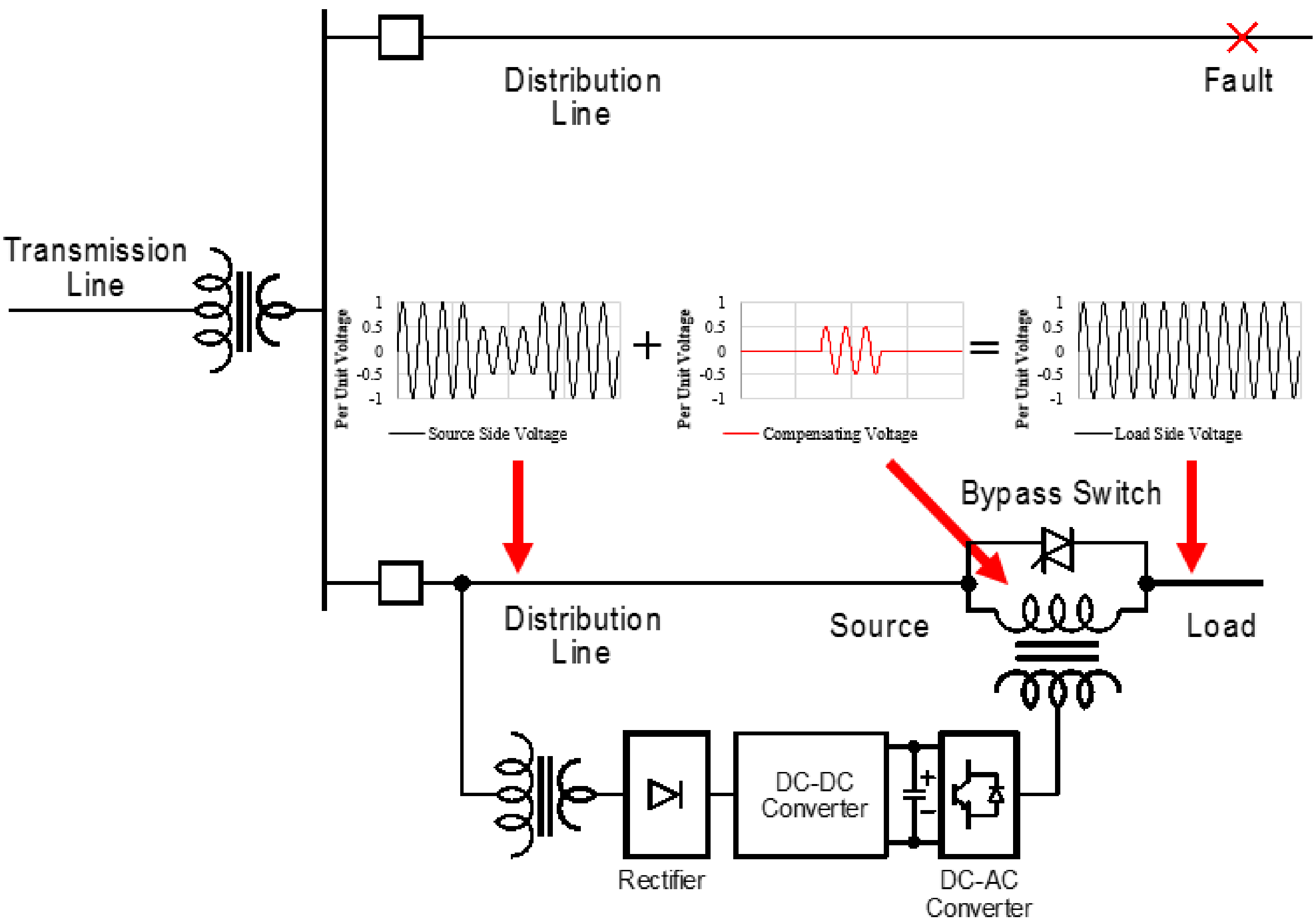

Fig. 19. Dynamic voltage restorer (DVR).[7]

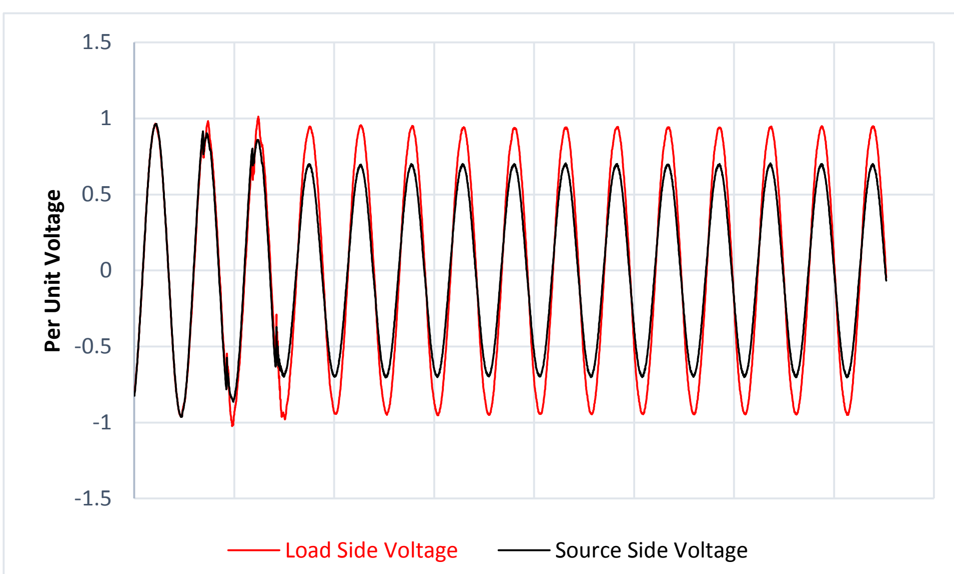

Fig. 20. Sag correction by a DVR (field performance).

A DVR is generally designed to store a certain amount of energy that can be used for voltage compensation for a certain amount of time. In another application, this may be a limitation. But this deficiency can be mitigated by a more general controller, which was designed in the 1980s and called an active power line conditioner (APLC).[8, 9]

The APLC introduced the concept of a shared dc link between two forced-commutated switch-based inverters, which are connected back-to-back at their joint dc link. One inverter is connected in shunt and another is connected in series with the line that supplies a load. These inverters exchange active power, P_{exch}, between them for continuous regulation of line voltage in distribution-level applications as shown in Fig. 21a.

The APLC extends the concept of an autotransformer, which is also a shunt-series configuration, meaning the exciter winding is connected in shunt and the compensating winding is connected in series with the line that supplies a load. The major difference between the two approaches is that the shunt and the series units in an autotransformer exchange active power as well as reactive power. However, in APLC, only active power is exchanged between the shunt and the series units. The same shunt-series inverters concept was used in the 1990s and 2000s in the design of the unified power flow controller for regulation of line power in transmission-level applications as shown in Fig. 21b.[1, 5, 10, 11]

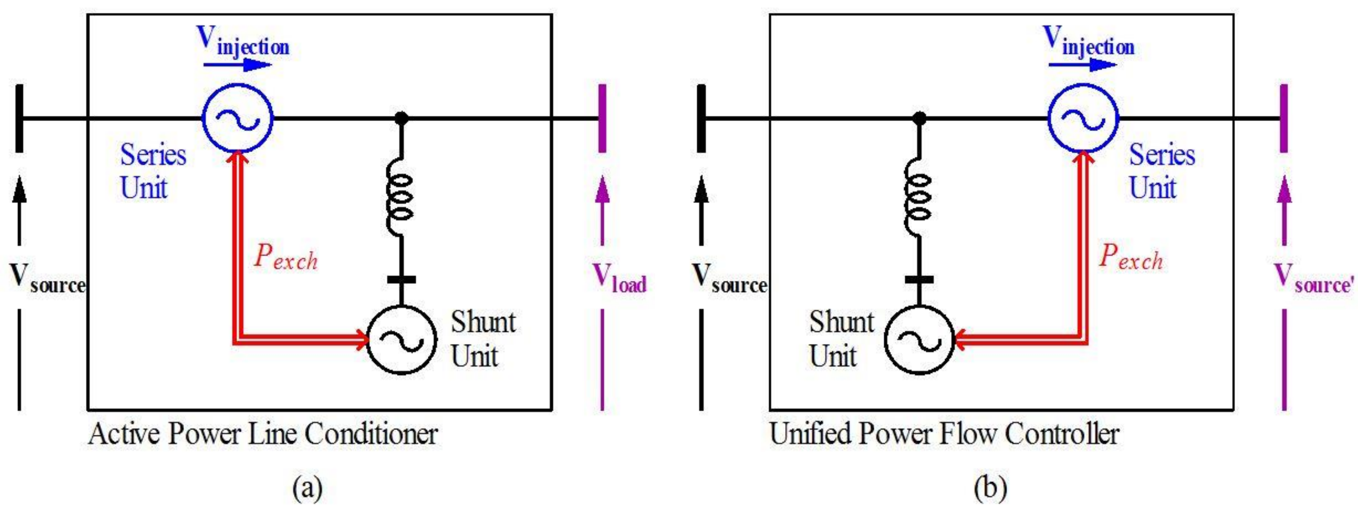

Fig. 21. Basic circuits for active power line conditioner[8] (a) and unified power flow controller[10] (b).

Defining A Cost-Effective Solution

Let us consider the previous cases of solutions for voltage regulation. Case 1: do nothing and the solution cost (cost #1) is zero; but the lost opportunity cost i.e., the cost of not providing a solution (cost #2) may be the highest as shown in Fig. 22.

Case 2: a shunt-connected inductor or capacitor with a breaker may seem to be the simplest solution with cost #1 that is greater than zero; but the lost opportunity cost (cost #2) that accounts for the benefits of providing var support and penalty for creating high transients may be less than that in case 1. Case 3: the solution cost (cost #1) increases for other options, such as synchronous condenser, SVC, STATCOM and so on; but the lost opportunity cost may actually go down.

Better solutions provide better regulation of voltage, thus creating less flicker and less penalty. In some cases, for example when a STATCOM is used, the voltage is so well regulated that the wear on the electrodes in an electric arc furnace application becomes more uniform than any previous solution and results in less frequent replacement of the electrodes, reducing the overall cost. When all the costs, benefits and penalties are taken into account, there may be a case where the cost of the added features of a particular solution outweighs the benefits. In between, there lies the cost-effective solution that provides the most features at the least total cost.

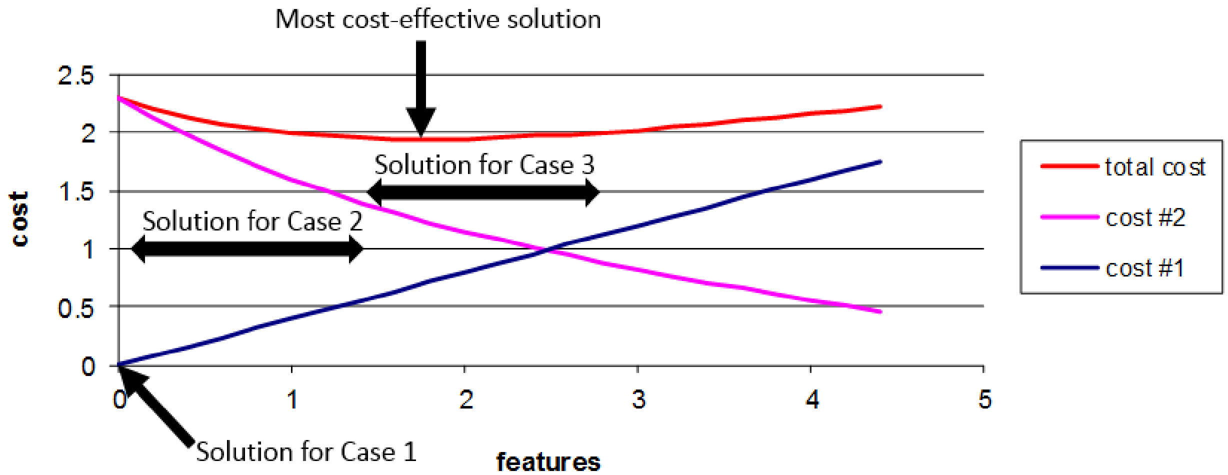

Fig. 22. Cost versus features in various solutions.

Conclusion

The voltage compensation in the line increases the active power flow over the natural flow when no compensation is applied. This results in higher line utilization, meets greater customer needs, integrates new sources of energy, and avoids building of new transmission lines, at least in the short term. The available solutions for voltage compensation range from using transformer and LTCs to power electronics, which can be divided into two categories: naturally-commutated switch-based solutions and forced-commutated switch-based solutions.

Each of these solutions is based on engineering tradeoffs. In particular, as the response speed of the solution increases from slow (seconds) to medium speed (cycles) to fast (milliseconds), there is a corresponding increase in the solution's cost (installation and maintenance), complexity and non-portability. Other important features to consider are reliability, efficiency and component non-obsolescence.

It is recognized that the superior response capability of a power electronics inverter-based solution may be beneficial in applications where voltage flicker is caused by an electric arc furnace load and dynamic voltage restoration is required for critical loads. The final selection of a solution, however, depends on knowing the functional requirements and analyzing the cost and benefit of each available solution to determine the cost-effective solution that provides the most features at the least total cost. In the case of a simple voltage regulation at a utility bus, a shunt capacitor may be an adequate solution; whereas for an arc furnace load, the power electronics inverter may be the best solution.

Acknowledgement

I would like to thank Dr. Tapan K. Manna of Burns & McDonnell Engineering and Dr. Albert Keri of ABB for their valuable comments in reviewing this document.

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About The Author

Currently the chief technology officer of Sen Engineering Solutions, Kalyan K. Sen has spent 28 years in academia and industry. Sen who was selected to be a Westinghouse Fellow Engineer, was a key member of the FACTS development team at the Westinghouse Science & Technology Center in Pittsburgh. He contributed in all aspects (conception, simulation, design, and commissioning) of FACTS projects at Westinghouse. Sen conceived some of the basic concepts in FACTS technology. He has more than 25 patents and publications in the areas of FACTS and power electronics, including a book and three book chapters. Sen also co-authored "Introduction to FACTS Controllers: Theory, Modeling, and Applications," Wiley/IEEE Press, 2009, which is now translated in Chinese. Sen co-founded Sen Engineering Solutions, which is dedicated to developing SMART Power Flow Controllers—a functional requirements-based and cost-effective solution. In addition, he is a licensed Professional Engineer in the Commonwealth of Pennsylvania.

Sen received BEE, MSEE, and PhD degrees in electrical engineering, from Jadavpur University, Tuskegee University, and Worcester Polytechnic Institute, respectively. In addition, he received an MBA from Robert Morris University. A senior member of IEEE, Sen has served the organization in many positions. In 2003, he reestablished the Pittsburgh chapters of the Power & Energy Society and the Industry Applications Society. Both chapters received the "Outstanding Large Chapter" awards for their activities in 2004. Under his chairmanship, the Pittsburgh section received the "Outstanding Large Section" award for its activities in 2005. His other past positions include Editor of the IEEE Transactions on Power Delivery (2002 – 2007), Technical Program Chair of the 2008 Power & Energy Society General Meeting in Pittsburgh, Chapters/Sections Activities Track Chair for the 2008 IEEE Section Congress, Quebec City, Power & Energy Society Region 2 Representative (2010, 2011) and Member of IEEE Center for Leadership Excellence (CLE) Committee (2013, 2014). He has been serving as an IEEE PES Distinguished Lecturer since 2002. In that capacity, he has given presentations on power flow control technology at over 90 places around the world. Currently, Sen is serving as the founding chair of the IEEE Pittsburgh Power Electronics Society Chapter, which has won the 2015 Best Chapter Award. He is an inaugural class (2013) graduate of the IEEE CLE Volunteer Leadership Training (VOLT) program. Sen is the recepient of the IEEE Pittsburgh Section PES Outstanding Engineer Award (2004) and Outstanding Volunteer Service Award for reviving the local chapters of PES and IAS from inactivity to world-class performance (2004).

