Voltage Regulation using Tap changing Transformers

A Project Report

submitted by

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THESIS CERTIFICATE

This is to certify that the thesis titled **Voltage Regulation using Tap changing Transformers**, submitted by **RISHI KUMAR, EE13B098**, to the Indian Institute of Technology Madras, for the award of the dual degree of **Bachelor of Technology and Master of Technology**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

It is imperative to independently control active and reactive power flow in a transmission line for the transfer of bulk power along a fixed path in the most cost-effective way. Sen Transformer uses transformer and tap changers that are traditionally used to build a voltage-regulating transformer (VRT) and a phase angle regulator (PAR). The ST regulates the voltage at a point in the transmission line as a VRT does. Additionally, the ST provides an independent and bidirectional active and reactive power (P and Q) flow control in the transmission line as a voltage-sourced converter (VSC)-based unified power flow controller (UPFC) does. Although both the ST and the PAR use a comparable number of components, the ST provides an area of controllability in the P-Q plane similar to a UPFC, while the PAR provides a linear P-Q characteristic. The technology of transformer and tap changer is proven to be reliable and cost-effective when compared with the emerging technology of VSC. ST is adequate to provide independent control of active and reactive power flow in most utility applications.

Among power flow controllers, Sen Transformer (ST) is one of the most attractive option. It has a wide control range, independent active and reactive power flow control capability, and is economically attractive. But Sen transformer operates in stepwise mode, has limited operating points, relatively slow response rate, and has compensation errors.

The other option we have is PST. They protect lines, make grids more reliable, and reduce transmission losses. And they are among the most economic and cost-efficient solutions for power-flow management.

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ABBREVIATION

ST - Sen Transformer

PST - Phase Shifting Transformer

UPFC - Unified Power Flow Controller

OLTC - On-load tap changers

FACTS - Flexible Alternating Current Transmission System

DG - Distributed Generation

DNO - Distribution Network Operator

IG - Induction Generator

AC - Alternation Current

PT - Potential Transformer

SE - State Estimation

CHAPTER 1

Introduction

In the last few years, operation of a transmission grid was relatively easy. Countries had designed their Grids to supply electricity within the country of origin and sometimes to support neighbouring countries in times of need. Also there was no need for large capacities at the border, because most of the energy was supplied by power plants within the country itself.

But the deregulation of the electricity market has led to major changes. In recent years, the number of DGs connected to the distribution networks is continuing to grow. Their impact on the network is therefore demanding proper attention and is affecting the design of new voltage technique scheme. The transmission grid is used as a transport medium between a producer (P) and consumer (C), which may or may not be in the same country. What actually is happening that P and C have concealed a contract which states that P produces a certain amount of energy and that C buys this energy. Hence, the contractual path of the electricity is straight. from P to C. The physical path, however, is a group of parallel paths, some of which lead through countries that are not involved in the contract. In this manner, uncontrolled power flows can occur in the transmission system of a country and overload its lines. Another problem that can occur is the uneven loading of parallel transmission lines.

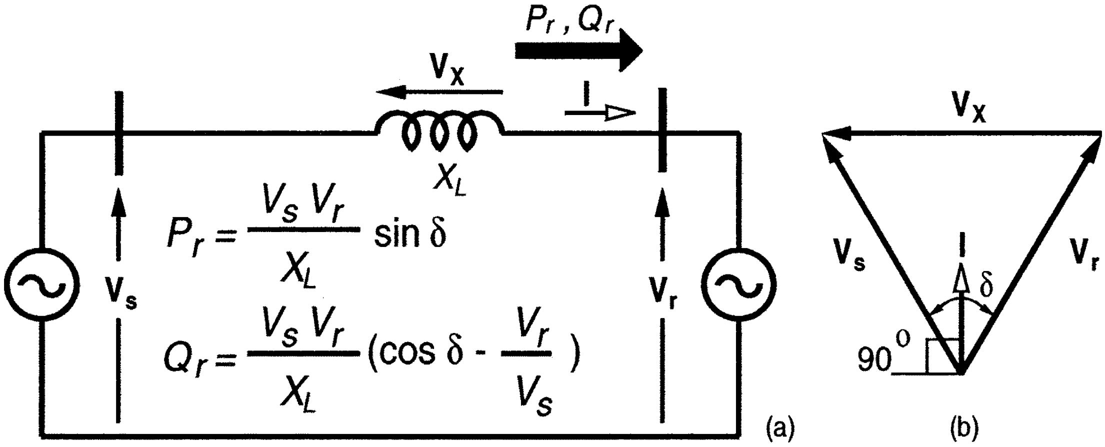

Figure 1.1: (a) Simple power transmission system and (b) phasor diagram.

As we know, the distribution of the power flow between two parallel lines is governed by their impedances which means that the line with the smallest reactance carries the largest part of the load. In most situations, one of the two lines will be operating well below its nominal rating because otherwise the parallel line would be overloaded.

In the two problems stated above, active power flow needs to be controlled. And it can be done by using Sen transformer or Phase Shifting Transformer.

Due to many factors that have arisen flexible power flow control in electric power trans-mission networks is very important. Among power flow controllers, Sen Transformer(ST) is one of the most attractive option. It has a wide control range, independent ac-tive and reactive power flow control capability, and is economically attractive. But Sentransformer operates in stepwise mode, has limited operating points, relatively slowresponse rate, and has compensation errors.

Sen Transformer uses the same main components (windings and taps) that are used in a phase shifting transformer.Sen Transformer (ST) is one of the most attractive options to control power flow. It provides independent active and reactive power flow control capability with a large control range and it is also economically attractive.

The other option we have is PST. They protect lines, make grids more reliable,and reduce transmission losses. And they are among the most economic and cost-efficient solutions for power-flow management. Phase shifting transformer changes the phase of the line. Thereby controlling either real or reactive power flow. PST doesn't control both real and reactive power flow. In terms of power flow control terminology,PST is limited to a set of linear operating points inside the circular PQ characteristic of Sen transformer.

Phase shifting transformers are widely used for the control of power flow over parallel transmission lines. Power flow control becomes necessary in today's deregulated power system market, when parallel transmission paths are owned or operated by different operators. PST offers a complete, reliable and more economical solution for the control of power flow as compared to FACTS devices. PSTs are available in unique designs and constructions when compared to the standard power transformers.

CHAPTER 2

Tap-changing transformers in Power Distribution System

When the load in a power network is increased the voltage will decrease and vice-versa. To maintain the network voltage at a constant level, power transformers are usually equipped with an on load tap changer (OLTC). The OLTC alters the power transformer turns ratio in a number of predefined steps and in that way changes the secondary side voltage. Each step usually represents a change in LV side no-load voltage of approximately 0.5 - 1.7 % . Standard tap changers offer between 19 to 35 positions.

The automatic voltage regulator (AVR) is designed to control a power transformer with a motor driven on-load tap-changer. Typically the AVR regulates voltage at the secondary side of the power transformer. The control method is based on a step-by-step principle which means that a control pulse, one at a time, will be issued to the on-load tap-changer mechanism to move it up or down by one position. The pulse is generated by the AVR whenever the measured voltage, for a given time, deviates from the set reference value by more than the preset deadband (i.e. degree of insensitivity).Time delay is used to avoid unnecessary operation during short voltage deviations from the pre-set value.

When the load in a power network changes it consequently affects voltage profile at load end. To maintain the load voltage within permissible limits, Power transformers are equipped with tap changing system. The tap changer alters transformer turns ratio in a number of predefined steps which results change in secondary side voltage (Load end).On load tap changing power transformers are an essential part of any modern power system ,since they allow voltages to be maintained at desired levels despite load changes. The problem with conventional tap changer is its mechanical structure of complicated gear mechanisms of selectors, diverters and switches. The on-load tap changer (OLTC) has a significant influence on voltage stability. Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal conditions and after being subjected to a disturbance, increase in load

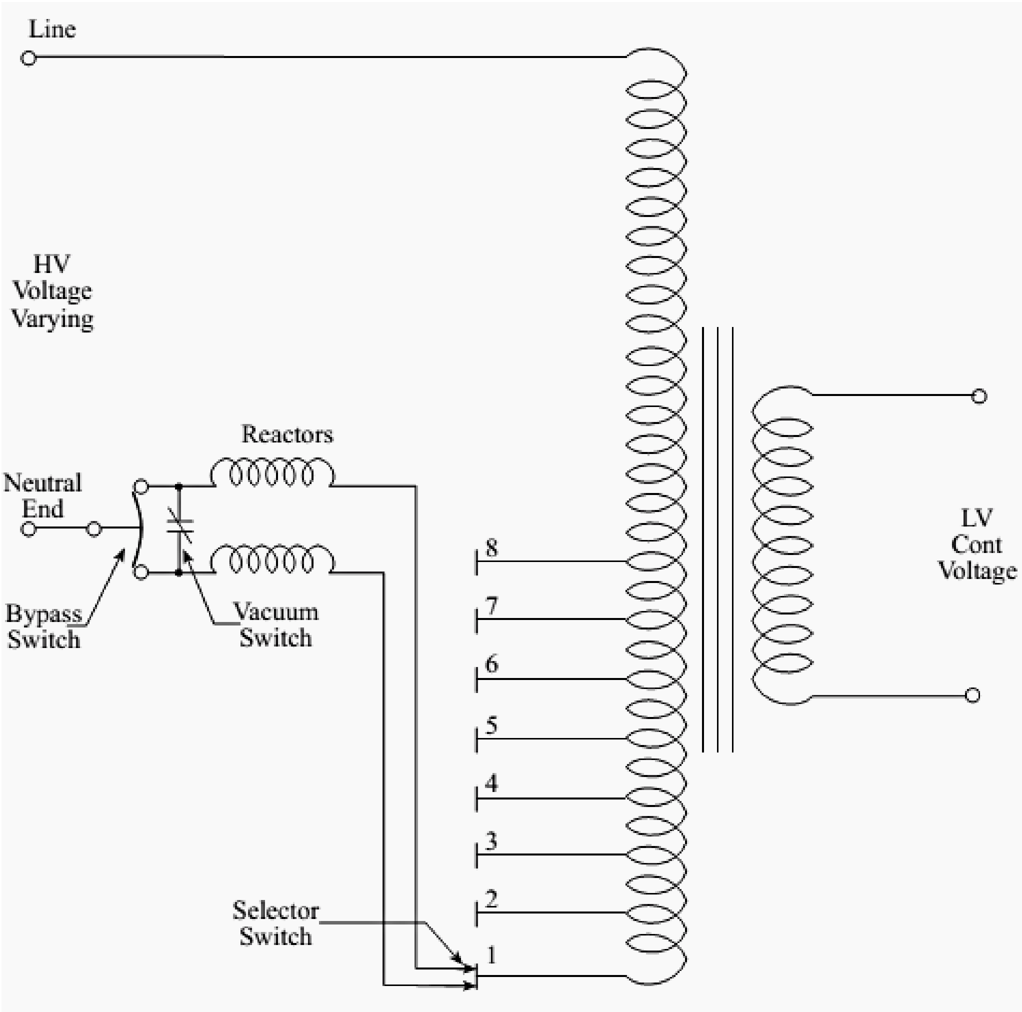

Figure 2.1: On-Load Tap Changer

demand, or change in system condition causes a progressive and uncontrollable decline in voltage. The main factors causing instability are the inability of the power system to meet demand for reactive power.

A large number of distribution systems have run into problems such as poor voltage regulation, poor power factor, high losses and poor efficiency, overloading and less reliability for continuity of supply. The main function of the AVR (automatic voltage regulation) system is to ensure the security and stability operation of the power system, and ensure that the voltage and power factor of the specific buses are within the preset values, and also minimize line reactive transmission, reduce the power loss of the grid due to unnecessary reactive power flow. The AVR system provides real time automatic control for the on-load transformer tap changer (OLTC).

Most network power transformers/autotransformers and large voltage regulators are equipped with manual or automatic on-load tap-changers (OLTC) so that the voltage ratio and hence the secondary voltage may be varied as the load supplied by the transformer changes. Manual control may be used for transformers whose tap positions are changed only infrequently, such as transformers at generating stations. Manual control may be local, at the substation or remote, at a central control center. Automatic control is provided on transformers in the high-voltage networks. On load tap changers (OLTCs) maintain a constant transformer secondary voltage given changing primary voltage and transformer load. A common OLTC arrangement has 16 taps above and below the nominal tap (33 total taps), and each tap adjusts the transformer turns ratio by 0.375 percent. When the transformer's secondary voltage is outside the permitted margin, thus motors change the tap position and regulate secondary voltage while still supplying the load. An OLTC control measures the secondary voltage and sends raise and lower signals to the OLTC motor to control secondary voltage.

The OLTCs interact with each other whenever there is a voltage deviation on the system. Traditionally, each voltage level is graded with the next, using simple time delays. This ensures that the upstream tap changers take priority over the downstream units and make their tap changes first. This prevents hunting and reverse actions by lower-level tap changers. Unfortunately, the voltage control can become crude and inefficient at small voltage deviations. The new control strategies have been developed to improve the coordination of the AVR system and hence provide an improved quality of supply for consumers.

2.0.1 Voltage Control with On-load Tap-changer

The ratio of a transformer can be changed by adding turns to or subtracting turns from either the primary or the secondary winding using a load tap-changer (LTC). The LTC can be located at the primary or the secondary side of the transformer. The representation of a transformer equipped with an LTC and its equivalent diagram is shown in the below figure. Notation I, U, n and y in the figure indicates current, voltage, normalization of the transformer turn ratio and transformer admittance, respectively; and subscripts p and s indicate primary and secondary sides of the transformer, respectively.

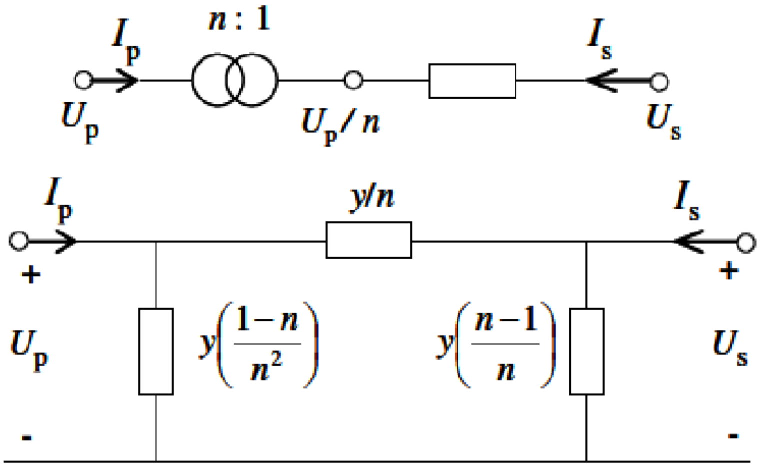

Figure 2.2: OLTC representation and its equivalent diagram

There are two types of LTC, no-load tap-changer where the transformer ratio can be changed only when the transformer is de-energized, and on-load tap-changer (OLTC) where changing of the tap position is possible also when the power transformer is carrying load.

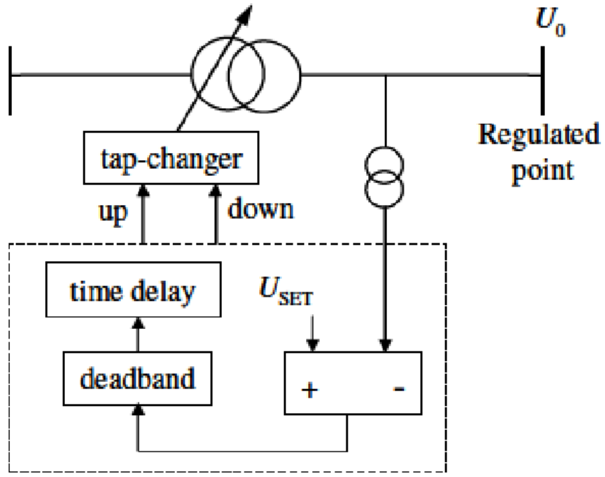

Figure 2.3: Basis OLTC arrangement

In oil-type OLTCs there are two types of switching principles used, the diverter which consists of an arcing switch and a tap selector, and the selector which consists of an arcing tap switch. Diverter type OLTCs change taps in two steps: First, the next tap is pre-selected by the tap selector at no load (Then the arcing switch transfers the load current from the tap in operation to the pre-selected tap. The tap selector is operated directly by the OLTC drive mechanism, whereas the arcing switch is operated by a stored energy spring.

2.0.2 Automatic OLTC Control Principles for Single Transformer

A typical AVR measures the busbar voltage (UB) at the power transformer LV side, and if no other additional features are enabled (i.e. line drop compensation) this voltage is used for voltage regulation. The voltage control algorithm then compares UB with the set target voltage (Uset) and decides which action should be taken. Because this control method is based on a step-by-step principle, a deadband U (i.e. degree of insensitivity) is introduced in order to avoid unnecessary switching around the target voltage. The deadband is typically symmetrical around Uset as shown in Figure 4. Deadband should be set to a value close to the power transformer.s OLTC voltage step. Typical setting is 75 % of the OLTC step.

During normal operating conditions the busbar voltage UB, stays within the deadband. In that case no actions will be taken by the AVR. However, if UB becomes smaller than U1 or greater than U2 (see Figure 4), an appropriate lower or raise timer will start. The timer will run as long as the measured voltage stays outside the inner deadband. If this condition persists for longer than a preset time, the appropriate LOWER or RAISE command will be issued. If necessary, the procedure will be repeated until the busbar voltage is again within the inner deadband. The main purpose of the time delay is to prevent unnecessary OLTC operations due to temporary voltage fluctuations. The time delay may also be used for OLTC co-ordination in radial distribution networks in order to decrease the number of unnecessary OLTC operations. This can be achieved by setting a longer time delay for AVRs located closer to the end consumer and shorter time delays for AVRs located at higher voltage levels.

CHAPTER 3

Voltage regulation and Control using OLTC

Voltage is an important parameter for the control of electrical power systems. The Distribution Network Operators (DNO) have the responsibility to regulate the voltage supplied to consumer within statutory limits. Traditionally, the On-Load Tap Changer (OLTC) transformer equipped with automatic voltage control (AVC) relays is the most popular and effective voltage control device. STATCOM, power factor generator are alsothe useful technique to control the voltage in distribution system. Connecting Distributed Generation (DG) to the network inherently affects the feeder voltage profiles and influences the voltage control in distribution systems.

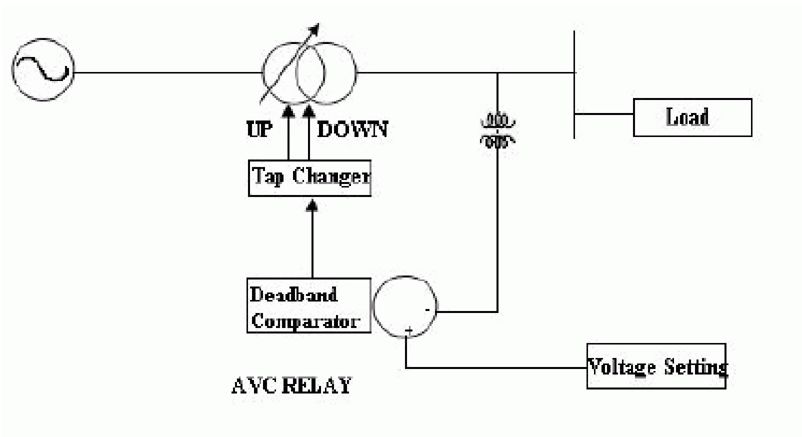

Figure 3.1: AVC relay Scheme

In recent years, the number of DGs connected to the distribution networks is continuing to grow. Their impact on the network is therefore demanding proper attention and is affecting the design of new voltage technique scheme. The potential for using Smart Grids also promises to have a major influence on schemes for voltage control in the power systems. .

Now a days the electrical power transmission and distribution system normally operated at multiple voltage level. Voltage is one of the most important parameter for the control of power system when connected to DG. The connection of DG in distribution system has created a challenge for distribution network operator to change their usual passive approach to an active system. The conventional distribution networks are designed based on the assumption of unidirectional power flow with the increasing connection DG. The network has become more dynamic with bidirectional power flow. It is known as active distribution network. An active distribution network is defined as distribution network with system in place to control a combination of distributed energy resource comprising of generator and storage. Voltage controls in active distribution system have been decomposing into three hierarchical level i.e. primary, secondary and tertiary levels. The primary control is performed by AVR (Automatic Voltage Regulator), the secondary control is performed by on load tap changer (OLTCs) meanwhile tertiary control is a short operation planning is developed to coordinate the action of primary secondary control device according to secured operation and economic criteria based on load and generation forecast. On the other hand voltage control in distribution system is normally achieved by in cooperating on load tap changer (OLTCs) and switched shunt capacitor only in most distribution system .

The voltage and reactive power equipment in distribution system are mostly operated based on and assumption that the voltage decreases along the feeder on the other connection of distribution generation will fundamentally alters the feeder voltage profile which will obviously effect the voltage control in distribution system . The modernization of electricity distribution system now a day coordinated voltage control developed into distribution system. Different method of short term operation planning for distribution system voltage control have been proposed. In the presence of DG.the distribution networks become more complex and the number of distributed generation (DG) is continuing to grow, conventional OLTC voltage control schemes are going to be less effective. Whenever there is reverse power flow caused by the integration of distributed generation, there are complications for the operation of the AVC. Meanwhile, the potential use of Smart Grids also indicates to have a significant influence on schemes for voltage control in the power systems. To deal with the voltage control problems together with the increasing penetration of the DGs as well as the use of Smart Grid, DNOs need more stable and effective OLTC voltage control schemes and also the other voltage schemes.

The most common voltage control technique on the distribution network is to use OLTCs which maintain a stable secondary voltage by selecting the appropriate tap position. It is an effective way to control the voltage magnitude. It is usually done with the help of Automatic Voltage Control (AVC) relay and Line Drop Compensation (LDC)

. The AVC relay continuously monitors the output voltage from the transformer; a tap change command will be initiated when the voltage is above the pre-set limits. The LDC is used to compensate additional voltage drop on the line between the transformer and load location, particularly, in the far end of the feeder. During heavy load, the controller boosts voltage the most, and during light load, voltage is boosted the least. The line-drop compensator uses an internal model of the impedance of the distribution line to match the line impedance. The user can set the R and X values in the compensator to adjust the compensation. The controller adjusts taps based on the voltage at the voltage regulating relay, which is the PT voltage plus the voltage across the line-drop compensator circuit. The task of the line drop compensation unit is to provide a voltage to the voltage regulator. Voltage from the line drop compensation unit is the measured voltage at the transformer, and the line current multiplied by a line drop impedance. Line drop compensation is used to control the voltage at a remote point, for instance at a selected point on a feeder or line.

Since load on a typical distribution line is distributed, R and X compensator settings are chosen so that the maximum desired boost is obtained under heavy load while a given voltage is obtained under light load. There are two main approaches for selecting settings:

1. Load center - The settings are chosen to regulate the voltage at a given point downstream of the regulator.

2. Voltage spread - The R and X settings are chosen to keep the voltage within a chosen band when operating from light load to full load.

The R and X settings may or may not be proportional to the line's R and X. In this paper we will look into the first method.

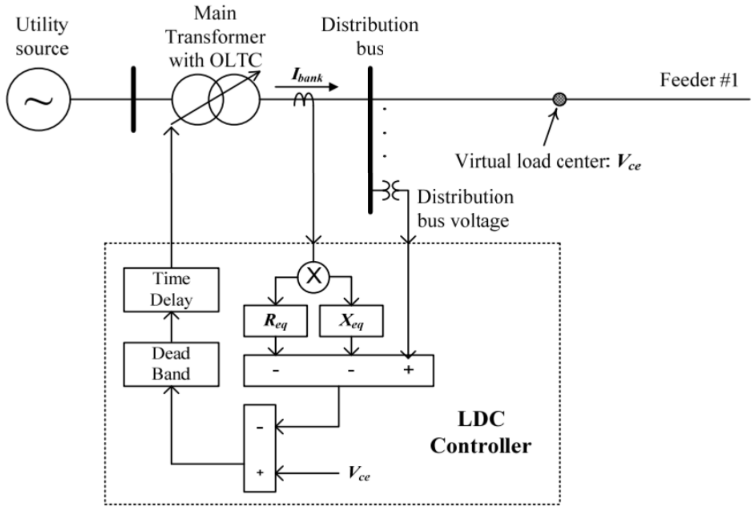

Figure 3.2: On-load Tap Changing (OLTC) transformer control schemes by Line Drop Compensation (LDC) method: OLTC transformer control mechanism.

In the LDC method, the sending-end reference voltage (SERV) is given by:

$$V_{ser} = V_{ce} + \Delta V \tag{1}$$

$$V_{ser} = V_{ce} + Z_{eq} * I_{bank} \tag{2}$$

Where

V_{ser} : sending-end reference voltage (SERV)

V_{ce} : reference voltage or voltage set value at virtual load center.

Z_{eq} : compensating impedance for voltage in line drop compensation (LDC) method.

I_{bank} : load current of the distribution substation transformer.

This voltage drop ΔV along the feeder impedance (line resistance R and line reactance X) is used to boost the voltage regulated at transformer terminal therefore ensuring the correct voltage level maintains at load where it is required. Properly adjusting R and X to the turns ratios of Current Transformer (CT) and Potential Transformer (PT) yields:

$$R_{eq} = (N_{CT}/N_{PT})R \tag{3}$$

$$X_{eq} = (N_{CT}/N_{PT})X \qquad (4)$$

where Req and Xeq are LDC simulated R and X settings for the resistive/reactive compensation. NCT is the turn's ratio of CT and NPT is turn's ratio of PT.

In Equation (1) $Z_{eq} * I_{bank}$ represents the equivalent voltage drop of the distribution lines. An intentional time delay, normally within 30 to 60 seconds, is always implemented in OLTCs so as to avoid unnecessary tap change operations during the transient voltage fluctuations. The tap change -operation usually takes 310 minutes to move from one position to another, and a several minute time interval between frequent operations is also required with considering the oxidation of tank oil.

In the steady-state, SEV can be determined by:

$$V_{se} = V_{tap,k} + Z_k * I_{bank} \tag{5}$$

Where -

Vse : sending-end voltage (SEV).

Vtap,k: secondary voltage of the OLTC transformer when a tap is located at the k-th position.

Zk: impedance of the OLTC transformer when a tap is located at the k-th position.

The SEV can be maintained by:

$$Vser - db < Vse < Vser + db \tag{6}$$

where db : dead band of LDC controller.

3.0.1 Impact of DG on LDC Control Method

If DGs are connected to a distribution system, the load current of the distribution substation transformer (Ibank) is changed to the following:

$$I_{bank'} = I_{bank} - \Sigma I_{DG} \tag{7}$$

where :

Ibank' : load current of the distribution substation transformer with DGs ΣI_{DG} : sum of injected current by all DGs.

From the above equation it is clear that the load current of a distribution substation transformer with DGs (i.e., Ibank ') is decreased due to the interconnection operations of the DG, which can affect the calculation of the equivalent voltage drop in the LDC controller. Therefore, the SERV with the interconnection operations of DGs becomes:

$$Vser = Vce + Zeq * Ibank \tag{8}$$

where , Vser': SERV with the interconnection of DGs.

Subtracting Equation (1) from Equation (8), the variation of the SERV with DGs can be obtained by:

$$\Delta Vser = Zeq * \Sigma I_{DG} \tag{9}$$

Where ΔV_{ser} : variation of the SERV due to the interconnection of DGs

In the same manner, the SEV with DGs becomes:

$$V'_{se} = V_{tap,k} + Z_k * I_{bank'} \tag{10}$$

where Vse' : SEV with the interconnection of DGs. Again Subtracting Equation (5) from Equation (10)

$$\Delta V_{se} = Z_k * \Sigma I_{DG} \tag{11}$$

where ΔV_{se} variation of the SEV due to the interconnection of DGs

CHAPTER 4

Voltage regulation and Control using Sen Transformer

Due to many factors that have arisen flexible power flow control in electric power transmission networks is very important. Among power flow controllers, Sen Transformer (ST) is one of the most attractive option. It has a wide control range, independent active and reactive power flow control capability, and is economically attractive. But Sen transformer operates in stepwise mode, has limited operating points, relatively slow response rate, and has compensation errors.

The ST uses time-tested components - transformers and tap changers, and injects a voltage of variable magnitude and phase angle, such as a UPFC, in series with the transmission line, thus regulating the active and reactive power flow in the line, independently.

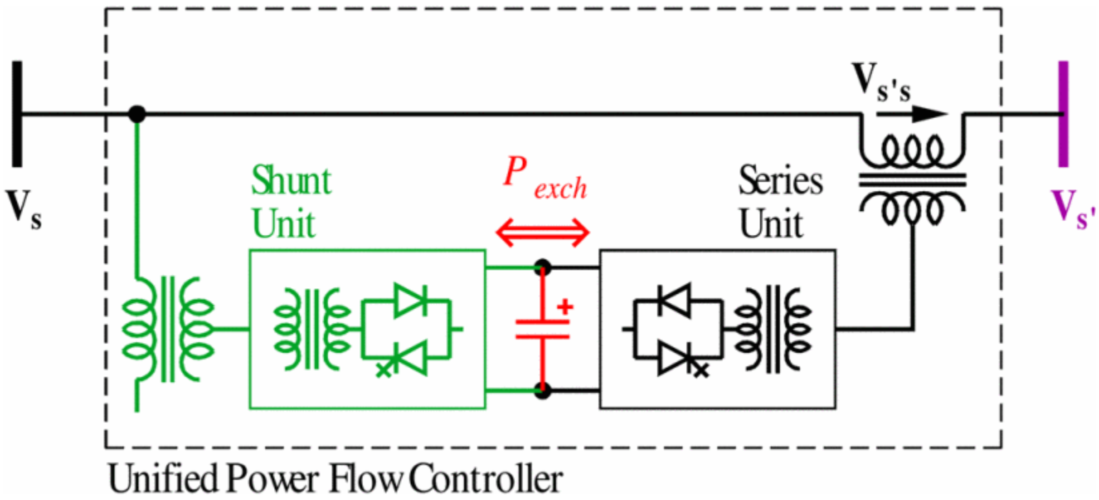

Figure 4.1: Unified power flow controller (UPFC).

$$P = \frac{V_s * V_r * sin\delta}{X_L} \tag{1}$$

$$Q = \frac{V_s * V_r * (cos(\delta) - \frac{V_r}{V_s})}{X_L} \tag{2}$$

where Vs is the magnitude of the sending-end voltage, Vr is the magnitude of the receiving-end voltage,δ is the difference in phase angle between the sending-end and the receiving-end voltages, and X_L is the reactance of the line. By changing any of these parameters, both active and reactive power flow can be regulated.

4.1 Working of Sen transformer

In a Sen transformer (ST), there are two units: exciter unit and compensating-voltage unit. The exciter unit consists of three primary windings (A, B, and C) that are Y-connected and placed on each limb of a three-limb, single-core transformer. The three-phase transmission-line voltage (V_{sA}, V_{sB}, V_{sC}) at the sending end is applied in shunt to the exciter unit. The compensating-voltage unit consists of nine secondary windings, three of which are placed on each limb of the core e.g., a1, a2, and a3 on the first limb, b1, b2, and b3 on the second limb, and c1, c2, and c3 on the third limb. The induced voltages from three windings that are placed on three different limbs are combined through series connection to produce the compensating voltage for injection in series with the transmission line, e.g., a1, b1, and c1 for injection in A-phase, a2, b2, and c2 for injection in B-phase, and a3, b3, and c3 for injection in C-phase. The number of active turns in the three windings can be varied with the use of on-load tap changers. As a result, the magnitudes of the components of the three 120 phase-shifted-induced voltages are varied and, therefore, the composite voltage , which is the phasor sum of the three induced voltages, becomes variable in magnitude and variable in phase angle in the range of 0 and 360 . It should be noted that each of a1, b2, and c3 is tapped at the same number of turns; each of b1, c2, and a3 is tapped at the same number of turns; each of c1, a2, and b3 is tapped at the same number of turns. However, the number of turns in the a1-b2-c3 set, b1-c2-a3 set, and c1-a2-b3 set can be different from each other.

A ST connects a compensating voltage Vs's of line frequency that is generated from the transformer's secondary windings connected in series. When connected in series with the transmission line, the compensating voltage of variable magnitude and variable angle modifies the magnitude and the angle of the sending-end voltage Vs to be the effective sending-end voltage Vs' and, therefore, controls the active and reactive power flow in the transmission line independently.

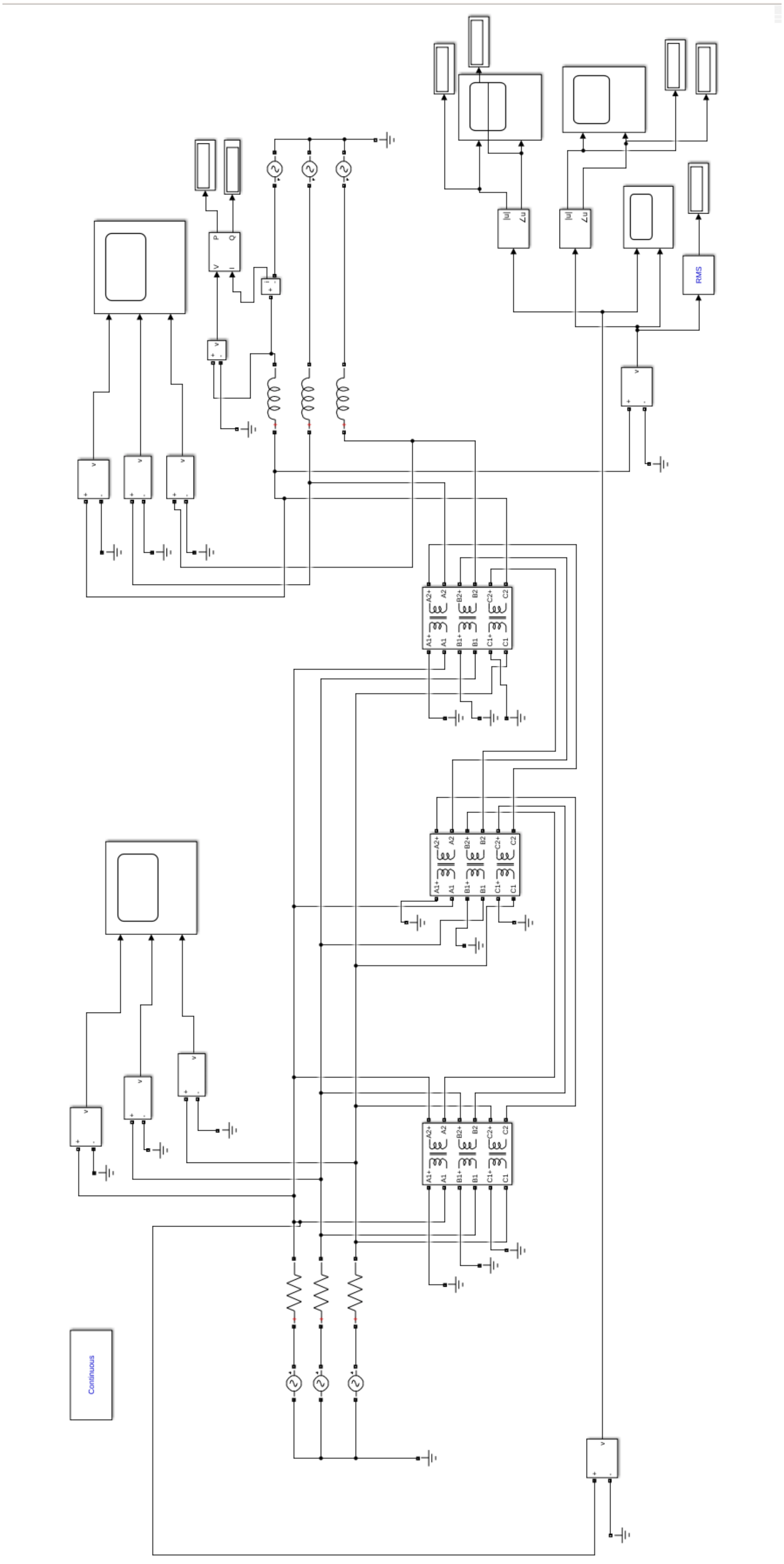

Figure 4.2: Model of Sen Transformer

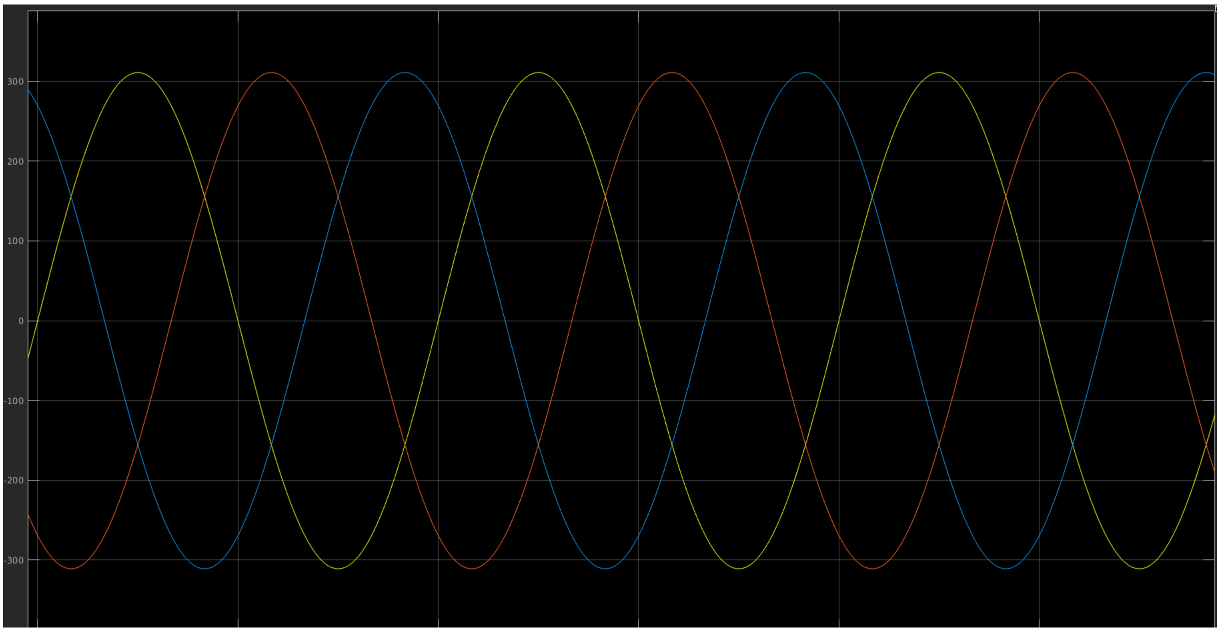

Figure 4.3: 3-phase input voltage in Sen Transformer

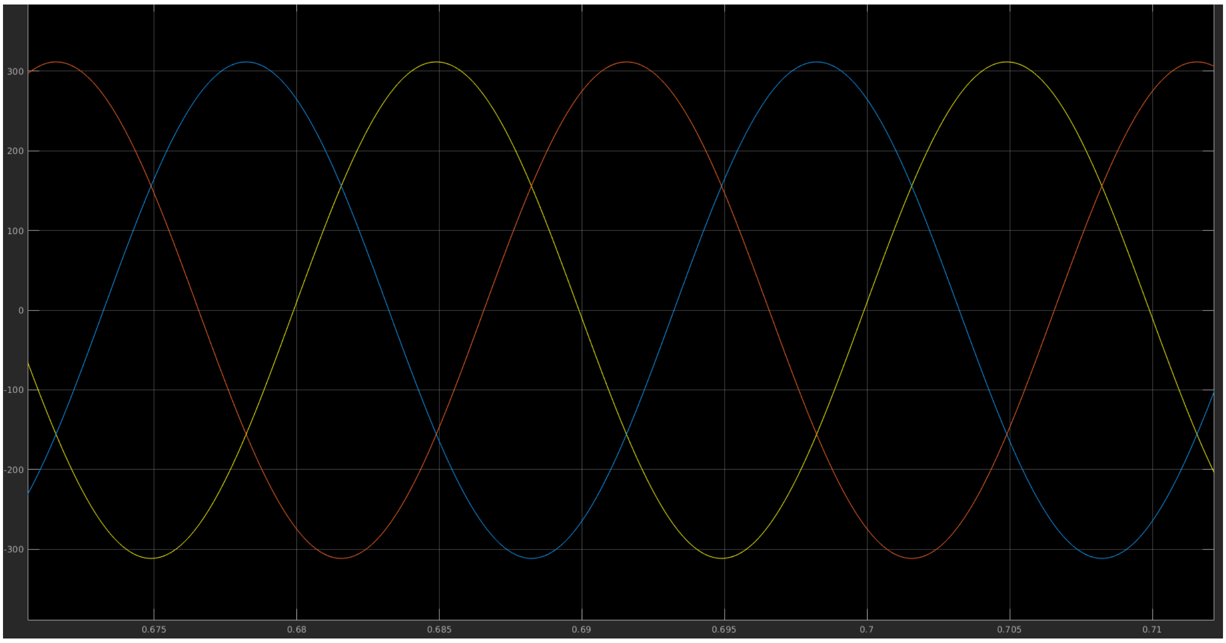

Figure 4.4: 3-phase output voltage from Sen Transformer

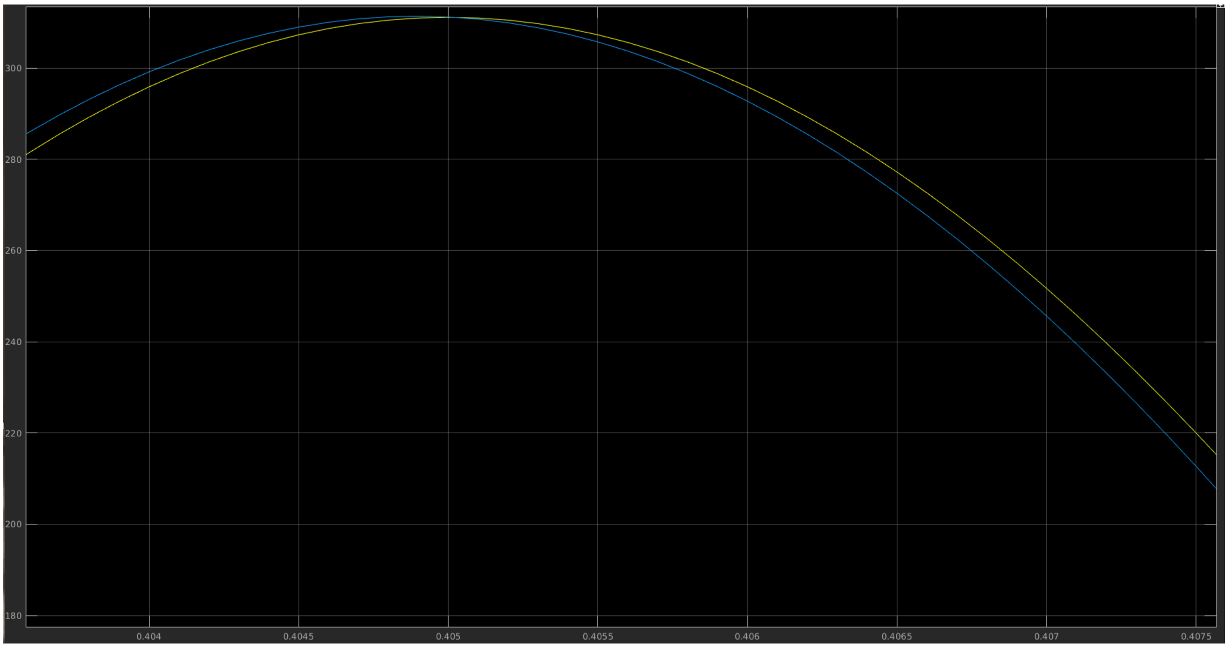

Figure 4.5: Phase difference introduced between the above two voltages.

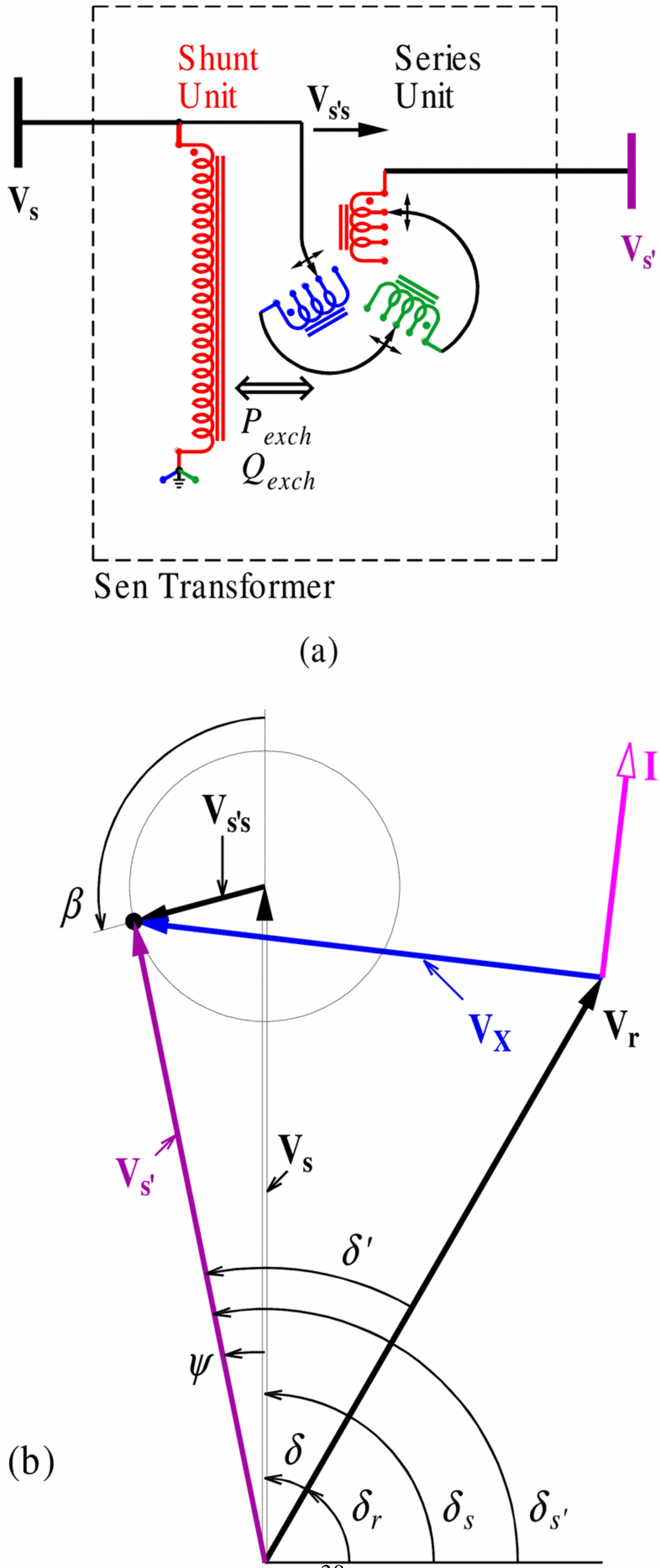

Figure 4.6: (a) Sen transformer and (b) the related phasor diagram.

4.2 Calculating compensating voltage (Vs's)

Let's assume $|V_s| = |V_r| = V$

initial angle between V_s and $V_r = \delta$

$$P_{ro} = \frac{V * V * sin\delta}{X} \tag{1}$$

$$Q_{ro} = \frac{V * V * (cos(\delta) - 1)}{X} \tag{2}$$

Power flow after adding the Compensating Voltage (Vs's) $\angle\beta$ is :

$$P_r = \frac{V * V * sin\delta}{X} + \frac{Vs's * V * sin(\delta + \beta)}{X} \tag{3}$$

$$Q_r = \frac{V * V * (cos(\delta) - 1)}{X} + \frac{Vs's * V * (cos(\delta + \beta)}{X} \tag{4}$$

Also,

$$Vs's = \frac{X}{V} * \sqrt{(P_r - P_{ro})^2 + (Q_r - Q_{ro})^2} \tag{5}$$

From equation 3, we get

$$\beta = \frac{(sin^{-}1(P_r - P_{ro} * X}{V * Vs's}) - \delta \tag{6}$$

Whereas from equation 4, we get

$$\beta = \frac{(cos^{-1}(Q_r - Q_{ro}) * X}{V * Vs's}) - \delta \tag{7}$$

Using concepts of inverse trigonometric ratios and the above two equations we can find out the correct value of β.

4.3 Algorithm for Splitting the Compensating Voltage into phasor components

The series compensating voltage Vs,s in any phase is derived from the contributions of the compensating windings of the ST from three different phases. If the phase angle of the series compensating voltage is exactly at 0 degree , 120 degree or 240 degree , it can be constructed from only one of the three phases a,c or b respectively. For any other angle, the series compensating voltage is constructed from two adjacent voltages.

Consider an ST, which has four tap positions in each of the nine compensating secondary windings. Each tap position provides a voltage of 0.1 p.u. and therefore, a maximum of 0.4 p.u. is obtained from each phase. The possible combinations of voltage tap-setting positions are shown by the dotted grid in. Let be the required compensating voltage, at an angle with reference to the corresponding phase angle. Then, one of the four combinations enclosed by the dashed circle must be selected. In addition, the selected combination must be the nearest to the voltage vector, Vs's .

The circle is shown in an enlarged view, where the four combinations marked as 1, 2, 3, and 4 are vector distances r1,r2 ,r3 and r4, respectively, apart from the desired series voltage Vs's . These four vector distances indicate the error introduced due to the selection of any particular combination. Of the four distances, the one with the least magnitude, will introduce the least error and the corresponding tap-setting combination would be selected to construct .

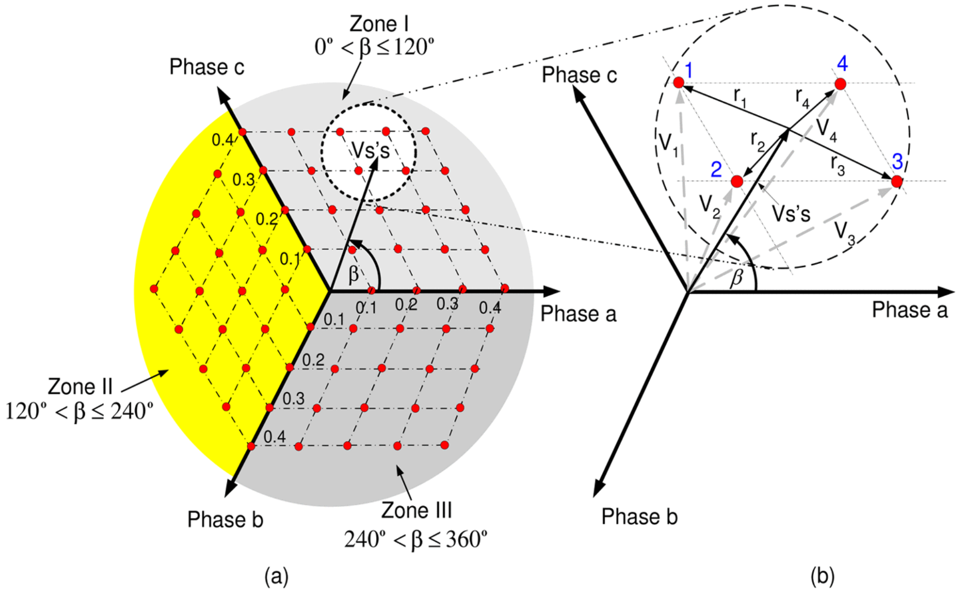

Figure 4.7: (a) Tap position grid for the construction of Vs's . (b) Selection of the best tap setting.

The tap-setting combination corresponding to with the smallest is selected as the best tap setting to implement. Thus, the algorithm to determine the best tap setting for consists of the following steps.

- Calculate the magnitude Vs's and leading phase angle Îš about required series voltage injection in phase a.
- Based on Îš, identify the zone into which the series voltage phasor falls: Zone I ($0 < \beta \leq 120$), Zone II ($120 < \beta \leq 240$) and Zone III ($240 < \beta \leq 360$).
- Based on the magnitude of Vs's, identify the four nearest tap-setting positions. Calculate the magnitude of errors $\epsilon_k (k = 1, 2, 3, 4)$ that would be introduced due to the selection of corresponding tap settings.
- Compare the errors and identify the tap-setting combination that yields the minimum error.
- Implement the tap setting in corresponding phase(s) in the ST through the use of load tap changers.

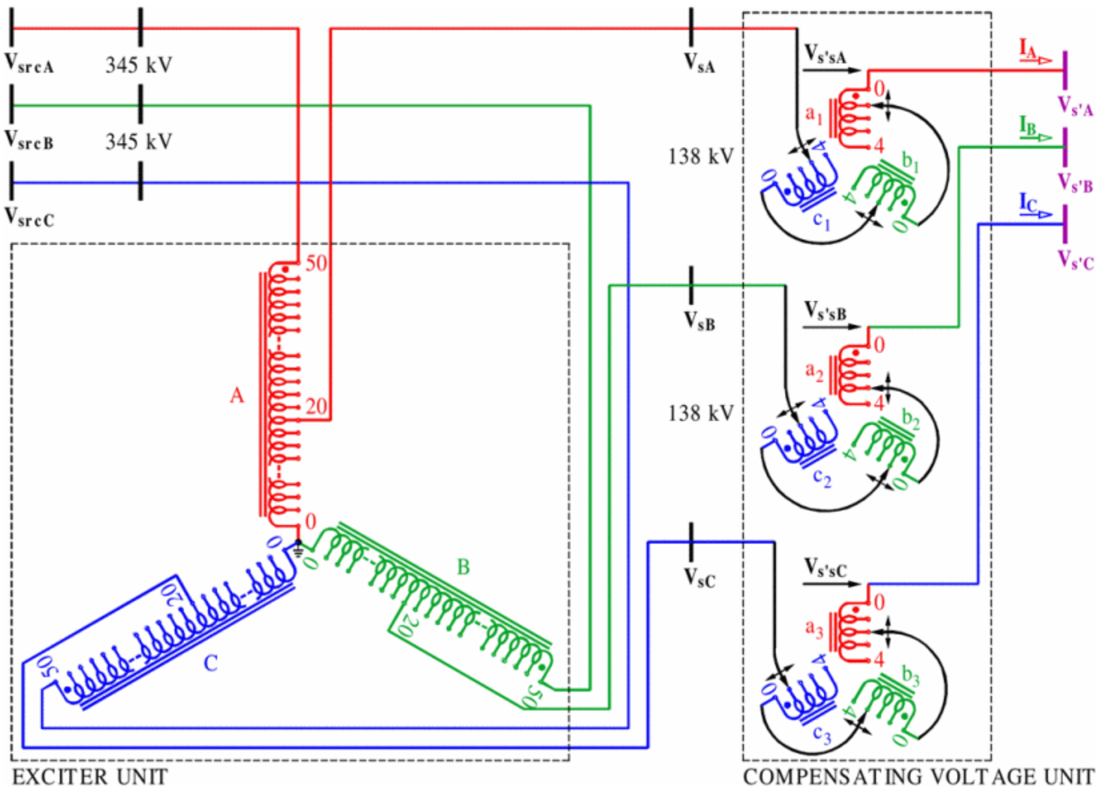

Figure 4.8: ST's compensating voltage unit is connected to the stepped-down voltage of a transmission line.

Due to many factors that have arisen flexible power flow control in electric power trans-mission networks is very important. Among power flow controllers, Sen Transformer(ST) is one of the most attractive option. It has a wide control range, independent ac-tive and reactive power flow control capability, and is economically attractive. But Sentransformer operates in stepwise mode, has limited operating points, relatively slowresponse rate, and has compensation errors.

CHAPTER 5

Voltage regulation and Control using Phase Shifting Transformer

Phase shifting transformers are widely used for the control of power flow over parallel transmission lines. Power flow control becomes necessary in today's deregulated power system market, when parallel transmission paths are owned or operated by different operators. PST offers a complete, reliable and more economical solution for the control of power flow as compared to FACTS devices. PSTs are available in unique designs and constructions when compared to the standard power transformers.

Phase shifting transformers are used to control the phase angle across the transformer. Since power flow through the transformer depends upon phase angle, this allows the transformer to regulate the power flow through the transformer

These transformers are available in various design and application types, depending on the power system application. Based on design and construction, they are available in two-core (indirect) and single-core (direct) constructions. Based on the application type, they can be categorized as symmetrical or asymmetrical. A symmetrical design alters the phase angle with equal magnitudes of source- and load-side voltages, whereas an asymmetrical design alters the phase shift and voltage magnitude, which can cause changes in the reactive power flow. The advantage of the symmetrical design over asymmetrical is that the phase shift angle is the only parameter that influences the power flow.

Operation of a transmission grid was relatively easy in the last few years. Grids were designed to supply electricity to its country of origin and sometimes to support neighbouring countries in times of need. And there was no need for large capacities at the border, because most of the energy was supplied by power plants within the country itself.

But the deregulation of the electricity market has led to major changes. The transmission grid is used as a transport medium between a producer (P) and consumer (C), which may or may not be in the same country. What actually is happening that P and C have concealed a contract which states that P produces a certain amount of energy and that C buys this energy. Hence, the contractual path of the electricity is straight. from P to C. The physical path, however, is a group of parallel paths, some of which lead through countries that are not involved in the contract. In this manner, uncontrolled power flows can occur in the transmission system of a country and overload its lines. Another problem that can occur is the uneven loading of parallel transmission lines.

As we know, the distribution of the power flow between two parallel lines is governed by their impedances which means that the line with the smallest reactance carries the largest part of the load. In most situations, one of the two lines will be operating well below its nominal rating because otherwise the parallel line would be overloaded. In the two problems stated above, active power flow needs to be controlled and the phase shifting transformer (PST) does just that.

5.1 Working of Phase Shifting Transformer

The active and reactive power transported over a transmission line is given by the following equations:

$$P = \frac{U_s * U_r * sin\delta}{X_L} \tag{1}$$

$$Q = \frac{U_s * U_r * (cos(\delta) - \frac{U_r}{U_s})}{X_L} \tag{2}$$

As it can be seen in the above equations that the active power is proportional to the voltages on the sending and the receiving side and to the sine of the electrical angle between both sides; it is also inversely proportional to the line reactance. Altering the active power can be done by altering the voltages, but this has a bigger influence on the reactive power, so this method is not very effective.

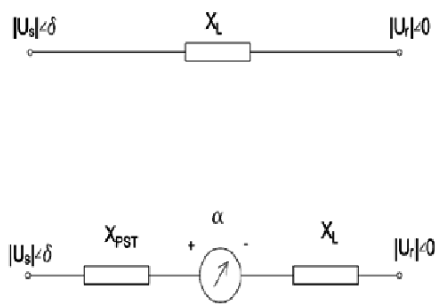

Figure 5.1: Model of a transmission line with and without a PST

The total line reactance can be lowered by placing a series capacitor in order to compensate for the inductance of the line. Besides the increased power flow, an additional advantage of this method is that oscillations can be damped by switching the capacitor at appropriate times.

Phase shift δ can be varied by adding the varying quadrature voltage ΔV between the two ends voltages. Assuming inductive load, the quadrature voltage must be 90 degree phase lag or lead to the load-side voltage. Therefore, phase shift can be advanced or retarded; advanced phase shift means that the load-side terminal voltage leads the source-side terminal voltage; retard phase shift means that the load-side terminal voltage lags the source-side terminal voltage.

The PST is modeled as a reactance in series with a phase shift. The power flow through the line is increased by adding an angle alpha to the existing angle delta. The phase shift is controllable within certain limits. Equation 1 becomes:

$$P = \frac{|U_s||U_r| \sin{(\delta + \alpha)}}{X_l + X_{PST}} \tag{3}$$

We can interpret the above equation stated in another way: the same amount of active power can be transported over the transmission line with a smaller value of δ. The graph of 3 is shifted by an amount α in comparison with 1, as can be seen in Fig.3.

The maximum power decreases by a factor $P = \frac{X_l}{X_l + X_{PST}}$ when using a PST.

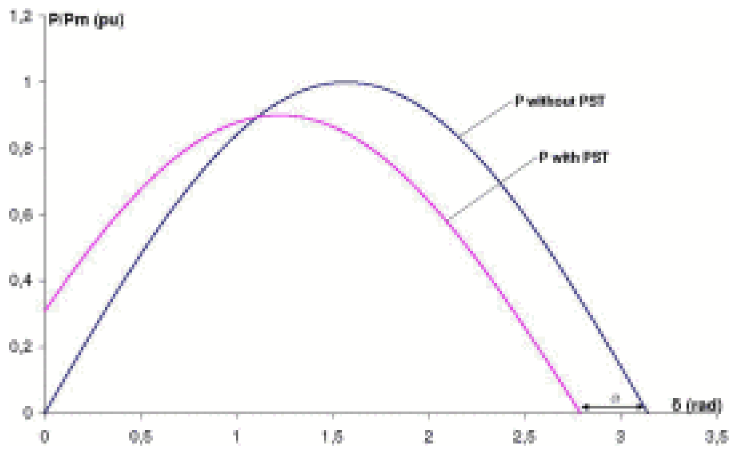

Figure 5.2: Active power as a function of δ with and without a PST

5.2 Types of PST

Phase shifting transformers are mainly categorized into two types, each with a different design and construction. Each design uses the same basic methodology to create the quadrature voltage by simply subtracting the other two phases from each other at the exciting winding, whereas the source and load sides are connected to the series winding.

5.2.1 Asymmetrical PST

Asymmetrical PST's create an output voltage with an altered phase angle and amplitude compared to the input voltage.

5.2.2 Symmetrical PST

Symmetrical PST's create an output voltage with an altered phase angle and amplitude compared to the input voltage.

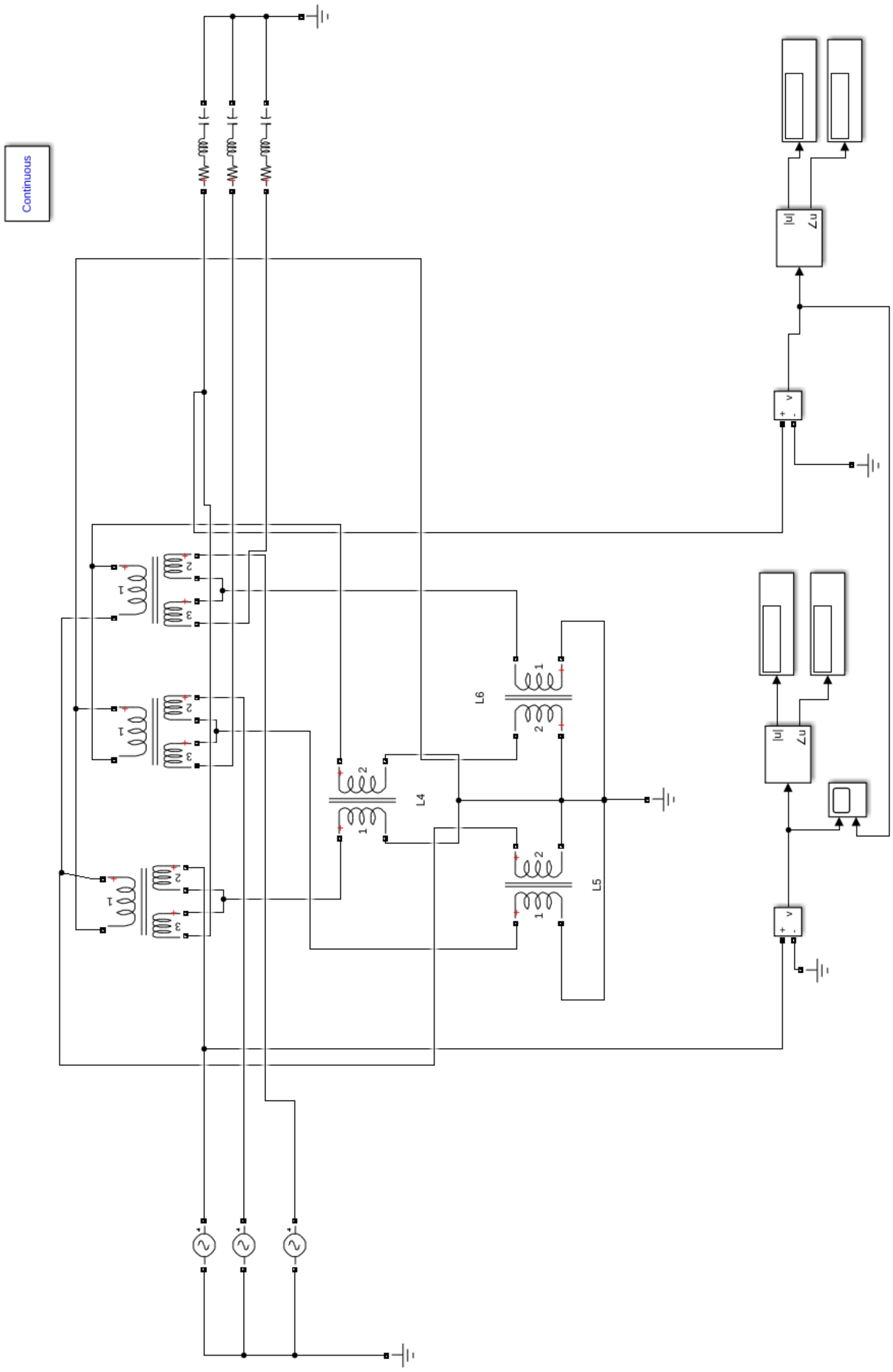

Figure 5.3: Schematic model of a two-core symmetrical PST

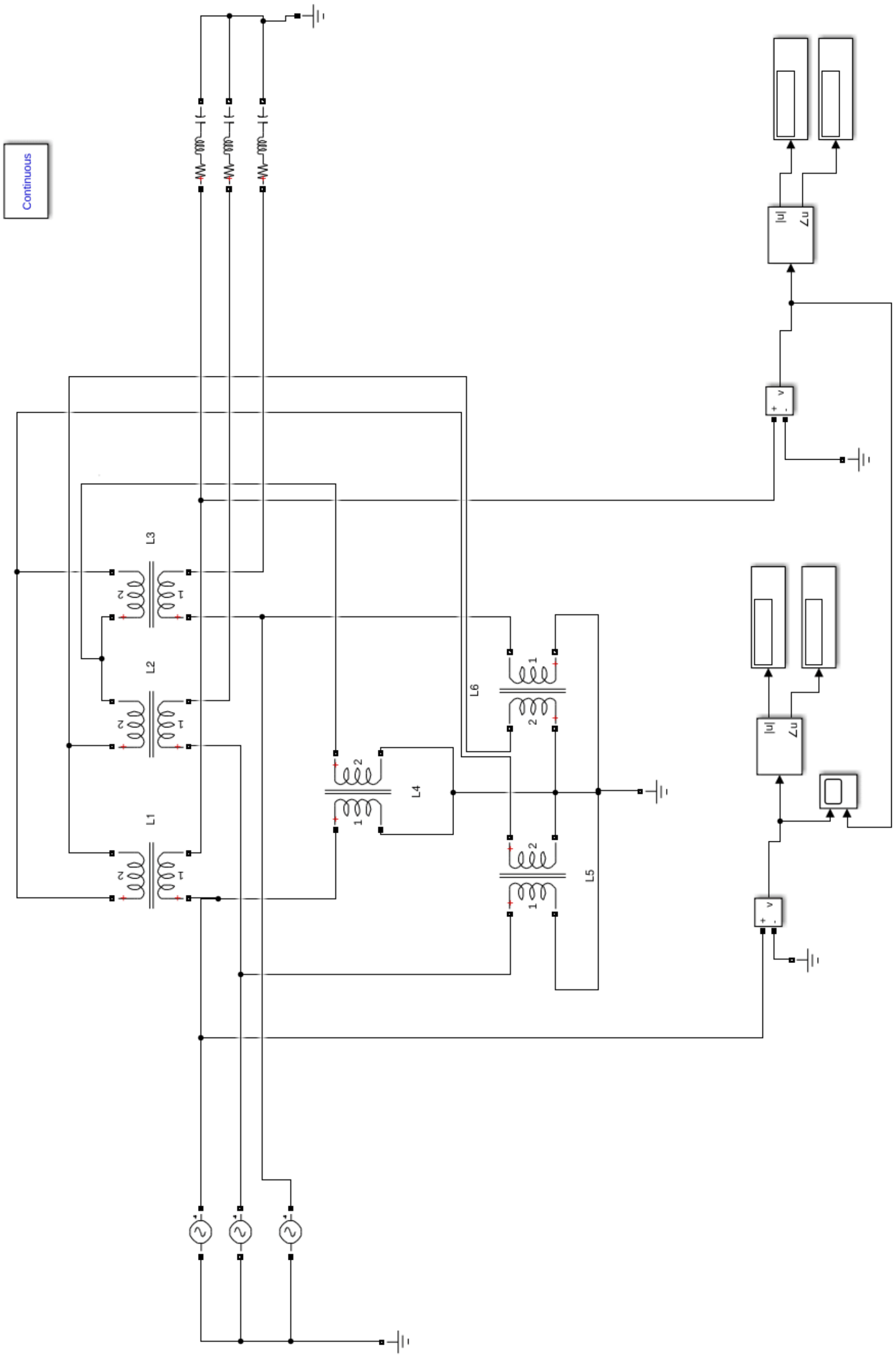

Figure 5.4: Schematic model of a two-core asymmetrical PST

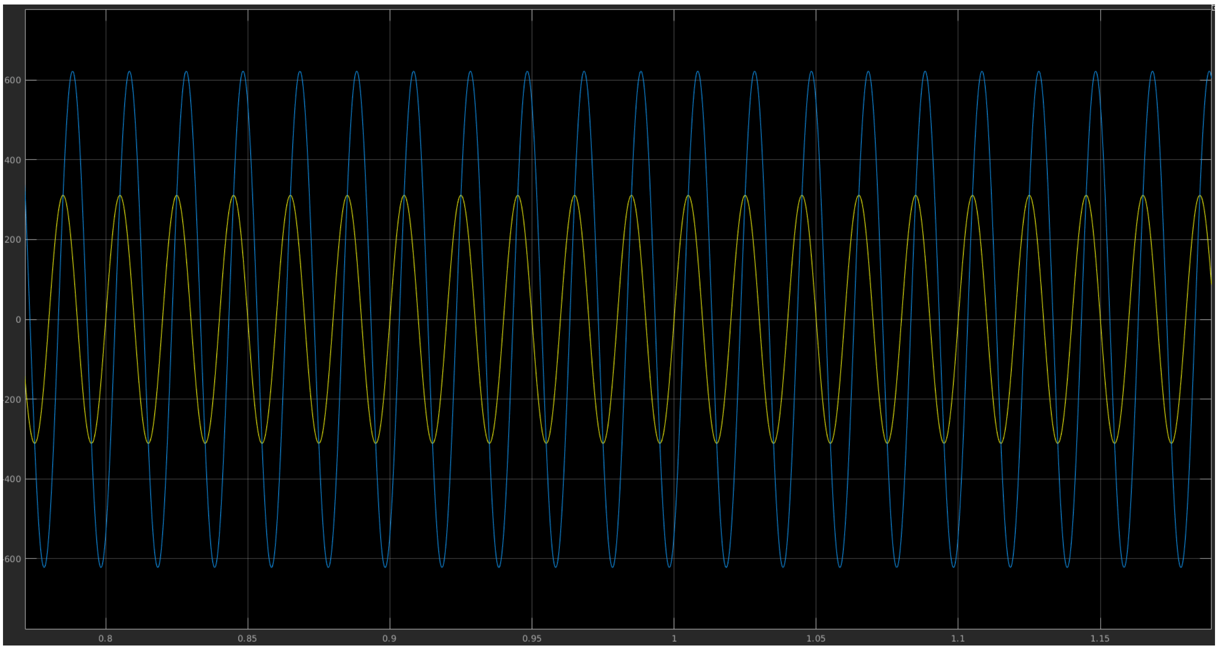

Figure 5.5: Phase shift introduced using Phase Shifting transformer.

As we can see in the above image that we can change the phase of input voltage (yellow line) and we got an output voltage (blue line), by using a PST. The drawback of a PST is that we can't control both the magnitude and phase of a voltage, as evident in the above figure. But if we use a Sen Transformer we can control both the magnitude and phase of a voltage.

5.3 Comparison of the topologies :

Asymmetric PSTs are obviously less complex when it comes to construction. This fact is also reflected in terms of cost. However, the fact that the voltage amplitude is altered is a major issue, making symmetrical topologies more popular. Furthermore, these symmetrical configurations can attain a larger angle than their asymmetric counterparts.

Summary :

Active power flow depends on the phase angle difference between the busses at both ends of the line, on the voltage magnitude at these busses and on the reactance of the line. Each of these three parameters can be influenced by a power flow controller. Recent innovations in power electronics have opened many doors in this particular field, but the PST is still a valuable alternative.

PSTs come in various implementations: a distinction can be made between symmetrical and asymmetrical types and between direct and indirect configurations. Classical modelling approaches include two-port equivalents, resulting in an asymmetrical admittance matrix, and the model of an ideal phase shift with a series reactance.

CHAPTER 6

Conclusion and Future Work

Among power flow controllers, Sen Transformer (ST) is one of the most attractiveoption. It has a wide control range, independent active and reactive power flow controlcapability, and is economically attractive. But Sen transformer operates in stepwisemode, has limited operating points, relatively slow response rate, and has compensationerrors.

Sen Transformer uses the same main components (windings and taps) that are used in a phase shifting transformer

The other option we have is PST. They protect lines, make grids more reliable, andreduce transmission losses. And they are among the most economic and cost-efficientsolutions for power-flow management. Phase shifting transformer changes the phase of the line. Thereby controlling either real or reactive power flow. PST doesn't control both real and reactive power flow. In terms of power flow control terminology, PST is limited to a set of linear operating points inside the circular PQ characteristic of sen transformer.

With the use of Sen transformer we can control both magnitude and phase of the line voltage. Thereby controlling both real and reactive power flow.

CHAPTER 7

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