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A Novel Approach of an Isolated Controlling Scheme for the Stability Enhancement of UPFC

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Abstract: ***The stability criteria in distributed power system are developed. The controller operation of a UPFC unit is proposed and an isolated controlling approach to shunt and series controlling operation is proposed. The observation of the isolated control operation illustrates a simple and effective approach for UPFC operation. The Stability criterion for the voltage parameter is proposed and evaluated.***

Keyword: Stability, power quality, UPFC, isolated shunt and series controlling.

I. INTRODUCTION

In recent years, voltage instability has been responsible for many major network collapses throughout the world; hence the growing interest of power engineers and researchers to address this problem. This chapter provides an introduction to the concepts and definitions related to voltage stability problems in power systems. "A power system at a given operating state is small-disturbance voltage stable if, following small disturbances, voltages near loads are identical or close to the pre-disturbance values." In other words we can say voltage stability is the ability of the system to maintain steady voltages in a pre-decided range (typically 1 p.u. ± 10 %) after being subject to a disturbance. The maximum power transfer limit of the network does not necessarily determine the voltage stability limit. In general, voltage stability involves disturbances of substantial magnitude. Such disturbances include large increases in loads and loss of heavily loaded lines, which leads to an increase in the amount of power transfer on other lines. The outcome of voltage instability is usually a progressive and uncontrollable voltage decay, which may lead to a complete voltage collapse (black out). The inability of the network to meet the reactive power demand is one of the major reasons for voltage instability. Voltage instability is most likely to occur in a highly stressed network, leading to a voltage collapse in some of its Parts and load shedding in other parts. Voltage instability is of much concern in a growing number of power systems. This is mainly due to the ever-increasing demand for power in conjunction with the inherent difficulties in building new transmission lines to transport power from remote generation units to load centers, consequently, the existing transmission networks are being operated closer to their stability or capacity limits.

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II. POWER FLOW CONTROLLING

A usual time frame for short-term voltage dynamics is up to ten seconds, approximately. The driving forces of this type of instabilities are the dynamic loads, which tend to restore the consumption of power and the system's power electronic devices, which tend to damp them in a time frame of seconds. Examples of such loads and devices include induction motors, HVDC and FACTS controllers and generator AVRs, to cite a few. Events falling under this short-term dynamics include induction motor stalling, oscillation of generators, and spikes due to switching on and off of devices. After the system sustains the disturbances causing short-term instability, other phenomena come into play. The latter operate in a time frame of a few minutes to a few tens of minutes. Few examples in this category are frequency problems resulting from generation-load imbalance irrespective of the network. One of the most effective ways to improve the power transfer capability and voltage stability of a system is reactive power compensation. There exist two classes of compensation methods. The first class is based on the connection type, namely series and shunt compensation, while the second class is based on the operation, namely, active and passive compensation. In active compensation, the voltage and other variables are controlled by a feedback control loops. Some common forms of reactive power compensation are series capacitors, shunt capacitor banks, series reactors, and static VAR compensators, to cite a few. As already discussed, one major aspect of voltage stability is the capability of a system to transfer reactive power from sources to sinks under steady operating conditions. Reactive power transmission is mainly dependent on the difference in nodal voltage magnitudes across the network. It flows from a higher to a lower voltage value. This is similar to heat transfer from an object at a higher temperature to a body at a lower temperature. Note that transmission of reactive power across large nodal voltage angles, even with substantial voltage magnitude gradients, may be difficult to achieve. Some of the reasons for minimizing transfer of reactive power through the network include the following:

A. To minimize the real and reactive losses for economic considerations. This can be illustrated by the following simple set of equations:

$$I^2 = \bar{I}\bar{I}^* = \left[\frac{P - jQ}{\bar{V}^*}\right]\left[\frac{P + jQ}{\bar{V}}\right] = \frac{P^2 + Q^2}{V^2}$$

$$P_{loss} = I^2 R = \frac{P^2 + Q^2}{V^2} R$$

$$Q_{loss} = I^2 X = \frac{P^2 + Q^2}{V^2} X$$

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Note that the real and reactive losses across the series impedance of the transmission line are given by I^2R and I^2X, respectively. Observing the above equations we can see that the losses are minimized when the reactive power transfer is low and the bus voltages are high;

B. To minimize the temporary over-voltage and hence, achieve a faster recovery, the reactive power transfer mainly determines the magnitude of the overvoltage;

C. Handling large amounts of reactive power consumed by the load requires equipment of larger size and rating, which leads to a higher cost of installation and operation. Shunt capacitor banks are one of the most inexpensive methods of reactive power compensation aimed at providing voltage support to the transmission system. They are usually connected to the buses rather than to the lines, with the primary purposes being voltage control and load stabilization. By correcting the receiving end power factor, these banks can be used up to a certain limit to effectively increase the voltage stability limits of the system and help in preventing voltage collapse in many situations. Mechanically-switched shunt capacitor banks have the advantage of much lower costs compared to the other methods of compensation like static VAR systems. However, they have a number of disadvantages and limitations from the voltage stability and control viewpoint. For example, unlike SVCs, they do not provide precise and rapid voltage control of the system. Also in systems heavily compensated by shunt capacitors, voltage regulation tends to be poor and stable operation is not possible beyond a certain level of compensation. The most important shortcoming of shunt capacitor banks is their inability to provide fast compensation under voltage contingencies. The reactive power output of these banks is proportional to the square of the voltage; consequently, in conditions where the voltage is dropping, the VAR support also drops, thus not serving its primary purpose. For transient voltage instability, the capacitor banks are not fast enough to prevent induction motor stalling. The UPFC is a generalized SVS represented at the fundamental frequency by controllable voltage phasor of magnitude Vpq and angle injected in series with the transmission line. Note that the angle ρ can be controlled over the full range from 0 to 2π . For the system, the SVS exchanges both real and reactive power with the transmission system. In the UPFC, the real power supplied to or absorbed from the system is provided by one of the end buses to which it is connected. This meets the objective of the UPFC to control power flow rather than increasing the generation capacity of the system.

A UPFC consists of two voltage-sourced converters, one in series and one in shunt, both using Gate Turn-Off (GTO) thyristor valves and operated from a common dc storage capacitor. This configuration facilitates free flow of real power between the ac terminals of the two converters in either direction while enabling each converter to independently generate or absorb reactive power at its own ac terminal. The series converter, referred to as Converter 2, injects a voltage with controllable magnitude Vpq and phase ρ in series with the line via an insertion transformer, thereby providing the main function of the UPFC. This injected voltage phasor acts as a synchronous ac voltage source that provides real and reactive power exchange between the line and the ac systems. The reactive power exchanged at the terminal of series insertion transformer is generated internally while the real power exchanged is converted into dc power and appears on the dc link as a positive or negative real power demand. By contrast, the shunt converter, referred to as Converter 1, supplies or absorbs the real power demanded by Converter 2 on the common dc link and supports the real power exchange resulting from the series voltage injection. It converts the dc power demand of Converter 2 into ac and couples it to the transmission line via a shunt connected transformer. Converter 1 can also generate or absorb reactive power in addition to catering to the real power needs of Converter 2; consequently, it provides independent shunt reactive compensation for the line. It is to be noted that the reactive power exchanged is generated locally and hence, does not have to be transmitted by the line. On the other hand, there exists a closed path for the real power exchanged by the series voltage that is injected through the converters back to the line. Thus, there can be a reactive power exchange between Converter 1 and the line by controlled or unity power factor operation. This exchange is independent of the reactive power exchanged by Converter 2.

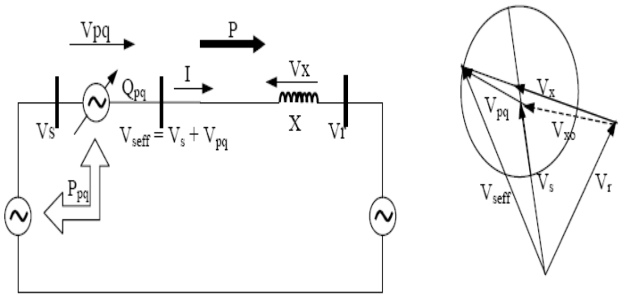

Fig. 1. Representation of the UPFC in a two-machine power system.

III. LINE CURRENT ANALYSIS

Even though spectral analysis, which is based upon the discrete Fourier transform, is a readily used technique for analyzing the spectral content of a signal, one might only be interested in the spectral content for particular frequencies that are not included in the discrete set of frequencies provided by the Fourier transform. This can happen when the number of samples is large and the number of frequencies of interest is much smaller. In this section we address the approximation of our signal, or time series, to a sum over a small set of frequency components. The frequencies of interest are known but the associated amplitude is not known. This will be accomplished using the method of least squares.

We begin by reviewing the method of least squares for determining the best fit of a line. The equation of a line only has two unknown parameters, the slope and the intercept. An understanding of the derivation for this simpler approximation should make that for the harmonic analysis more transparent.

We begin with a set of data, presented in the usual pairs (x_i, y_i) for $i = 1, \ldots, N$. We are interested in finding the best approximation, in some sense, of this data by some function. In the case of linear regression, we seek a linear relationship of the form $y = ax + b$. though this line is not expected to agree with the data, it is expected to be as "close as possible". What does one mean by "as close as possible"? We could mean that the total distance between the known data points and the line is as small as possible.

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Though there are many ways we could quantify this, the most natural would be to sum over the standard distance between the points for all data points. Thus, we would look at an expression like $\sum_{n=1}^{N}\sqrt{(x_i-x_i)^2+(y_i-(ax_i+b))^2}$. However, since the first term under the square root vanishes and the square root only returns a positive number, we could instead just consider the expression $\sum_{n=1}^{N}(y_i-(ax_i+b))^2$. making the later as small as possible only gives the same result as for the first expression, but is easier to compute. Thus, this leads to the phrase "least square" regression.We are interested in minimizing this quantity, which could be thought of as a variance about the straight line mean. We minimize this "error" by varying a and b. Thus, we have a two variable minimization problem. In order to minimize a function of one variable, we differentiate the function with respect to the variable and set it equal to zero to determine that value of the independent variable that yields a minimum. In this case, we need to simultaneously set the derivatives with respect to a and b to zero and find the values of a and b that solve the resulting equations.

Differentiating $\sum_{n=1}^{N}(y_i-(ax_i+b))^2$ with respect to a and b separately, gives

$$0=2\sum_{n=1}^{N}(y_i-(ax_i+b))(-x_i)$$

$$0=2\sum_{n=1}^{N}(y_i-(ax_i+b))(-1).$$

Regrouping, we find that these are simultaneous equations for the unknowns:

$$a\sum_{n=1}^{N}x_i^2+b\sum_{n=1}^{N}x_i=\sum_{n=1}^{N}x_iy_i$$

$$a\sum_{n=1}^{N}x_i+bN=\sum_{n=1}^{N}y_i.$$

Solving this system of equations gives expressions for a and b in terms of various sums over expressions the involving the data. This is the basis of the so called "best fit line" that is used in many programs, such as those in calculators and in MS Excel. However, we are interested in fitting data to a more complicated expression than that of a straight line. In particular, we want to fit our data to a sum over sin and cosines of arguments involving particular frequencies.

We will consider a set of data consisting of N values at equally spaced times, $t_n=n\Delta t, n=1,\ldots,N.$ we are interested in finding the best approximation to a function consisting of M particular frequencies, $f_k, k=1,\ldots,M.$ namely, we wish to match the data to the function

$$f(t)=A_0+\sum_{k=1}^{M}[A_k\cos(2\pi f_kt)+B_k\sin(2\pi f_kt)].$$

The unknown parameters in this case are the A_k 's and B_k 's. We will not determine a function that exactly fits the data, as in the DFT case, but only seek the best fit curve to the data. [Note: for simplicity of the results, we have redefined the constant term A_0.

In the following we will pick times $t_n=n\Delta t=\frac{nT}{N}$. Then $f_kt=f_kT\frac{n}{N}$. In the text, the authors let $\alpha_k=f_kT$, making $f_kt=\alpha_k\frac{n}{N}$. For now we will hold off from this notation.

To determine the unknowns, we need to minimize the "variance"

$$e^2=\sum_{n=1}^{N}[y(t_n)-(A_0+\sum_{k=1}^{M}[A_k\cos(2\pi f_kt_n)+B_k\sin(2\pi f_kt_n)])]^2.$$

To do so, we differentiate this expression with respect to all of the parameters. Namely, for a particular q, we have

$$0=\frac{\partial e^2}{\partial A_q}=2\sum_{n=1}^{N}[y(t_n)-(A_0+\sum_{k=1}^{M}[A_k\cos(2\pi f_k\frac{n}{N})+B_k\sin(2\pi f_k\frac{n}{N})])](-\cos(2\pi f_q\frac{n}{N})), q=1,\ldots,M$$

$$0=\frac{\partial e^2}{\partial B_q}=2\sum_{n=1}^{N}[y(t_n)-(A_0+\sum_{k=1}^{M}[A_k\cos(2\pi f_k\frac{n}{N})+B_k\sin(2\pi f_k\frac{n}{N})])](-\sin(2\pi f_q\frac{n}{N})), k=1,\ldots,M.$$

As with the previous example of a best fit line, we have here a system of linear equations for the unknowns. We can rewrite this system in a more apparent form and then make use of matrix theory for solving systems of equations.

$$A_0\sum_{n=1}^{N}\cos(2\pi f_qt_n)+\sum_{k=1}^{M}\left[A_k\sum_{n=1}^{N}\cos(2\pi f_kt_n)\cos(2\pi f_qt_n)+B_k\sum_{n=1}^{N}\sin(2\pi f_kt_n)\cos(2\pi f_qt_n)\right]=\sum_{n=1}^{N}y(t_n)\cos(2\pi f_qt_n),$$

and

$$A_0\sum_{n=1}^{N}\sin(2\pi f_qt_n)+\sum_{k=1}^{M}\left[A_k\sum_{n=1}^{N}\cos(2\pi f_kt_n)\sin(2\pi f_qt_n)+B_k\sum_{n=1}^{N}\sin(2\pi f_kt_n)\sin(2\pi f_qt_n)\right]=\sum_{n=1}^{N}y(t_n)\sin(2\pi f_qt_n),$$

for $q=1,\ldots,M$.

Finally, we need to consider the equations for $q=0.$ In this case we have

$$0=\frac{\partial e^2}{\partial A_0}=2\sum_{n=1}^{N}[y(t_n)-(A_0+\sum_{k=1}^{M}[A_k\cos(2\pi f_kt_n)+B_k\sin(2\pi f_kt_n)])](-1)),$$

which reduces to

$$\sum_{n=1}^{N}[(A_0+\sum_{k=1}^{M}[A_k\cos(2\pi f_kt_n)+B_k\sin(2\pi f_kt_n)])]=\sum_{n=1}^{N}y(t_n)..$$

We now note that we can write this system of 2M+1 equations in matrix form. We first define the $M\times N$ matrices C and S with elements

$$C_{qn}=\cos(2\pi f_kt_n), q=1,\ldots,M, n=1,\ldots,N$$

$$S_{qn}=\sin(2\pi f_kt_n), q=1,\ldots,M, n=1,\ldots,N.$$

The above sums over n can be written as the $M\times M$ matrix products with the entry in the qth row and kth column as

$$\left(CC^T\right)_{qk}=\left(\sum_{n=1}^{N}\cos(2\pi f_kt_n)\cos(2\pi f_qt_n)\right)$$

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$$\left(CS^T\right)_{qk} = \left(\sum_{n=1}^{N} \sin(2\pi f_k t_n)\cos(2\pi f_q t_n)\right)$$

$$\left(SS^T\right)_{qk} = \left(\sum_{n=1}^{N} \sin(2\pi f_k t_n)\sin(2\pi f_q t_n)\right)..$$

Here C^T is the transpose of C. Thus, $C^T{}_{ij} = C_{ji}$ and $\left(AB\right)^T = B^T A^T$.

Inserting these expressions into the system of equations, we have

$$A_0\sum_{n=1}^{N} C_{qn} + \sum_{k=1}^{M}\left[\left(CC^T\right)_{qk} A_k + \left(SC^T\right)_{qk} B_k\right] = \sum_{n=1}^{N} C_{qn} y(t_n),\ q = 1,\ldots M$$

$$A_0\sum_{n=1}^{N} S_{qn} + \sum_{k=1}^{M}\left[\left(SC^T\right)_{qk} A_k + \left(SS^T\right)_{qk} B_k\right] = \sum_{n=1}^{N} S_{qn} y(t_n),\ q = 1,\ldots M$$

and

$$A_0 N + \sum_{k=1}^{M} A_k c_k + B_k s_k = \sum_{n=1}^{N} y(t_n).$$

Finally, these equations can be combined by defining

$$y = \begin{pmatrix} y(t_1) \\ \vdots \\ y(t_N) \end{pmatrix},$$

$$Y = \begin{pmatrix} \bar{y} \\ Cy \\ Sy \end{pmatrix},\quad Z = \begin{pmatrix} A \\ B \end{pmatrix},\quad c_q = \sum_{n=1}^{N} C_{qn},\quad s_q = \sum_{n=1}^{N} S_{qn}$$ and

$$D = \begin{pmatrix} N & c^T & s^T \\ c & CC & CS \\ s & CS & SS \end{pmatrix}.$$

Note that Y and Z are 2M+1 dimensional column vectors, c and s are M dimensional column vectors and D is a $(2M+1)\times(2M+1)$ matrix.

The system of equations in matrix form looks like $DZ = Y$. Solving for the unknowns in the column vector Z, we have $Z = D^{-1}Y$.

IV. CONTROLLING STRATEGY

The ability of the UPFC to rapidly inject an ac-compensating voltage phasor with variable magnitude and angle in series with the line when needed, bestow it with superior operating characteristics. When equipped with suitable electronic controllers, the UPFC can not only establish an operating point within a wide range of possible P and Q flows on the line, but can also rapidly displace that operating point to another position. The shunt converter draws a controlled current phasor from the line, the real part of which is determined by the real power requirement of the series converter while the reactive part can be set to any desired level within the converter's capability. The shunt part of the UPFC has two modes of operation. The first operating mode achieves reactive power control. Here, the reference input is an inductive or capacitive Var request. This request is translated into a corresponding shunt current request by the shunt converter, which adjusts the gating of the converters to establish the desired current. The second operating mode achieves automatic voltage control. Here, the shunt converter reactive current is automatically regulated to maintain the transmission line voltage at the point of connection. The series converter provides control over the angle of the voltage phasor injected in series with the line. Dependent on the operation mode of the UPFC, the voltage injected controls the power flow on the line. This converter has four operating modes, which are the direct voltage injection mode, the line impedance compensation mode, the phase angle shifter mode and the automatic power flow control mode. They will be described next. In the direct voltage injection mode, the voltage is generated with the magnitude and phase as required by the reference input. One such example is the operation to purely supply reactive power to the system.

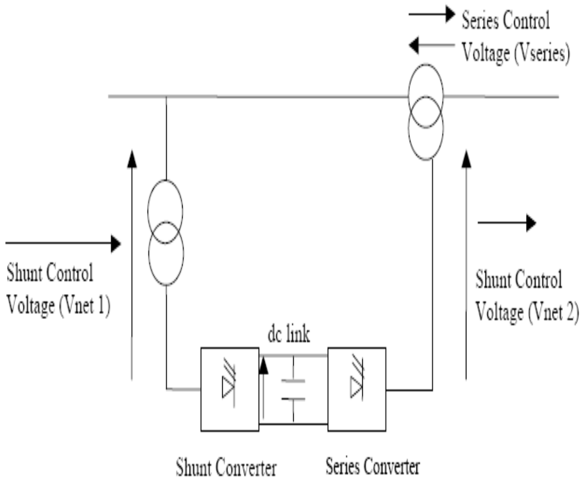

Fig. 2 Principle UPFC control scheme.

In the line impedance compensation mode, the magnitude of the injected voltage is controlled according to the magnitude of the line current in such a way that the series injection emulates a reactive impedance when viewed from the line. When the UPFC is operating in the phase angle shifter mode, the injected voltage is controlled with respect to the reference input so that the output bus voltage phasor is shifted by a certain angle. Lastly, when the UPFC is in the automatic power flow control mode, the magnitude and angle of the injected voltage phasor is controlled so as to adjust the line current to achieve the required real or reactive power flow. The control of the shunt part consists of two loops. One of these loops is the fast control of the dc-voltage at the capacitor terminals between the two converters. It has the fastest response and outputs the active current absorbed by the shunt part. The second loop provides a voltage control, outputting the reactive current to be supplied by the shunt part. The latter comprises of an integral-type control of the voltage generated by the shunt converter. The calculation of the active current supplied by this shunt part is done such that the total active power generated by the shunt part almost instantly matches that used by the series part. In addition, the shunt part has an undervoltage protection which brings the reactive power to zero when the threshold is exceeded. The shunt part's active current is given a certain priority to ensure that the capacitor voltage is being controlled more than the reactive power exchange.

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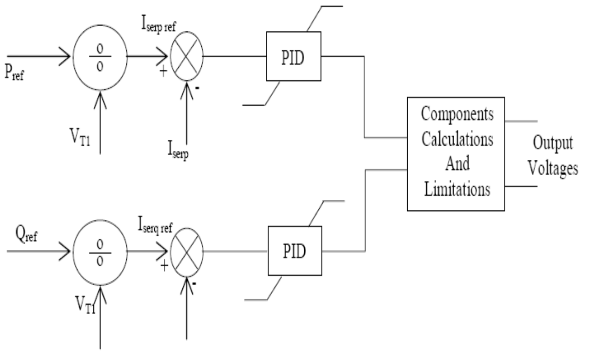
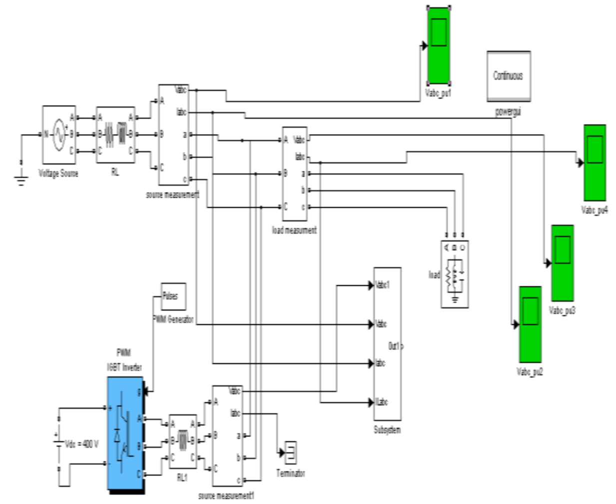
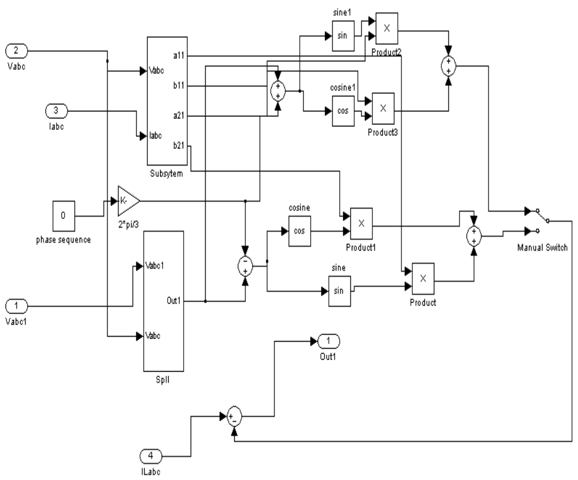


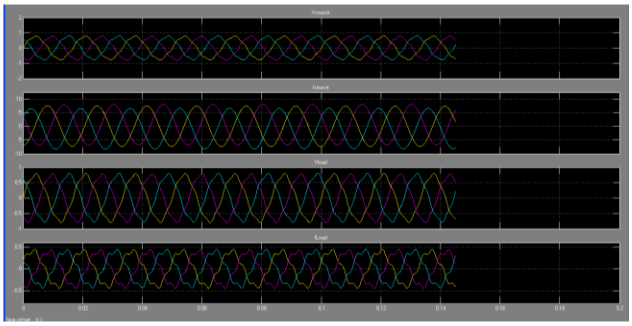
Figure 3: isolated controlling strategy

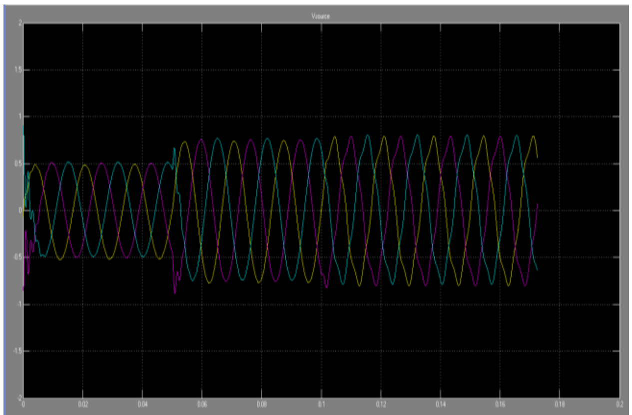
To summarize, the two injectors are governed by four Macroblocks, three of which are linked to the series injector and one to the shunt part. The first Macroblock comprises the control system, measurements, and setpoints, and outputs the phase and magnitude of the series injection voltage. The second macroblock comprises the dcvoltage control of the capacitor.

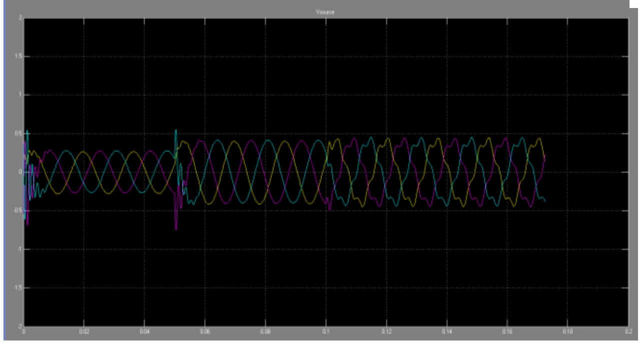
V. RESULT OBSERVATION

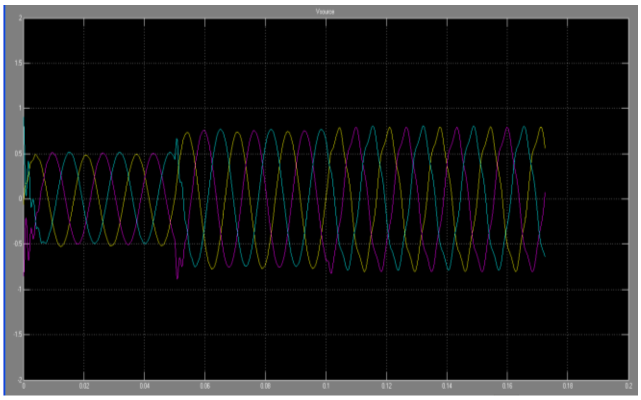


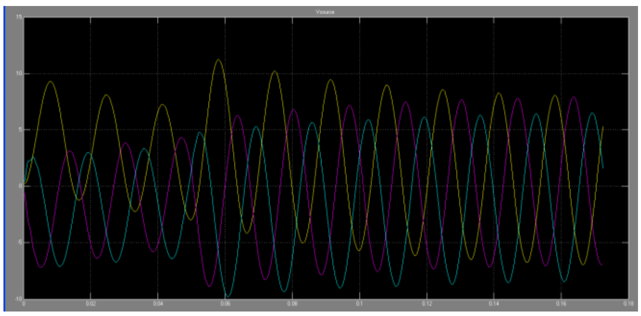












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VI. CONCLUSION

The instability problem has been addressed by the fine tuning of the UPFC, wherein the maximum loadability of the system has been increased by a considerable value, and thus enabling the system to operate closer to its thermal limits. This is owing to the presence of FACTS devices like the UPFC and SVC, which are fast and highly effective means of controlling the voltage and power flow on the network when appropriately tunes and coordinated. Control coordination of these devices is achieved by means of a two-level hierarchical control scheme. It serves as a centralized control that aims at damping the oscillations that may take place in the system should a single or a double contingency occur. The control scheme has increased the overall loadability of the network by a significant value as substantiated through simulations.

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