INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH & DEVELOPMENT

ISSN 2278 – 0211 (Online)

Estimating the Effect on Harmonic Impedance in a Low Voltage Network Due to Different FACTS Controllers

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Abstract:
Harmonic impedance is the equivalent spectral impedance of the power system which characterizes the frequency response characteristics of the particular system. This paper presents different considerations on harmonic impedance due to different FACTS devices in an effective and easy to implement method. This method uses a different FACTS device to create a controlled short circuit at the measurement point. The short circuit produces a pulse current and a voltage distortion, which are then used to estimate the system impedance. The strength of current pulse is controlled through the thyristor firing angle so that enough signal energy available for precise measurement and yet the disturbance is small enough not to cause any power quality problems. This method uses DFT analysis to extract the harmonic voltage caused by the FACTS devices.

Keywords: *Impedance, Power system harmonic, Flexible AC transmission system (FACTS) device, resonance.*

1. Introduction

The frequency response of a power system is an important parameter and is mainly used for designing harmonic filters, checking harmonic emission limits and predicting the system resonance. With the increased use of non-linear loads in the power system harmonic impedance studies are often performed in the network. Non-linear loads are generally characterized by the harmonic current and therefore to express the emission limits in terms of current rather than in voltage. In order to translate the injected harmonic into harmonic voltage through, one needs the harmonic impedance of the system.

With knowledge of harmonic impedance in supply mains we can forecast its ability of harmonic transfer, the risk of failure in case overload and the risk of resonance between the system and the load. It is an important parameter in planning the effective harmonic mitigation actions and in designing the harmonic filters. It also helps in maintain the system reliability and efficiency.

In many applications, harmonic impedance has to be measured online in order to identify the harmonic source. As a result many impedance measurement methods are proposed in the literature. All have to rely on variation of voltage and current variations at the driving point depending on the nature of the problem. Depending on the origin of harmonic voltage/current [2, 3] measurement methods can be broadly classified into two types, Non-Invasive method which uses harmonic current/voltage from existing sources or by switching process of network equipment [4, 5] and the second method is Invasive which uses an external source to inject harmonic current/voltage. The second method provides much control on the disturbances generated. This type methods can adjust the disturbance levels to improve measurement accuracy for different type of systems. For example [1, 6] proposes using a thyristor short circuit and an inverter to inject current into the supply system respectively. Here we using thyristor short circuit method [1] to inject current pulses into the system, which is easy method for implementation for small systems and consumes less amount energy than remaining methods [6, 7, 8].

Here we are discussing the influence of different FACTS devices on system impedance, by generating sufficient amount of current pulse to cause the voltage distortion by using FACTS device which are controlled by thyristor firing angle.

This paper is organized as follows: impedance measurement scheme is introduced in section 2. Basic description of FACTS device was discussed in section 3. Computer simulation is studied in section 4. Section 5 carries with conclusions.

2. Measurement Method

The basic principle in measurement harmonic impedance is to make use of harmonic current I_h inject at the point where the harmonic impedance Z_h is to be measured, then using ohm's law

$$Z_h = \frac{U_h}{I_h} \quad (1)$$

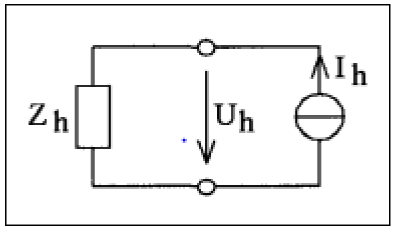


Figure 1: Basic principle of harmonic impedance.

Assuming that no harmonic voltage was present in the network prior to the current injection. In cases where assumption is not valid, U_h and I_h should be replaced by ΔV_h *and* ΔI_h. In practice however, the power system is three phase and is not symmetrical. Furthermore, in most cases the injected harmonic currents are far from symmetrical. Therefore the principle of transient based measurement is to be used.

2.1. Transient Based Harmonic Impedance Measurement

Consider a linear network disturbed by an external event. Transient signals show up on the terminal voltage and current waveform and decay to an in-discriminable level regarded as zero after period. This signals are recorded during the whole transient process and are denoted as $dv(t)$ and $di(t)$, respectively. According to the Fourier transform of non-periodic signals

$$dV_{dp}, dI_{thyristor}, dI_1 \text{ and } dI_2 \quad (2)$$

Where $dV(jw)$ and $dI(jw)$ are the Fourier transform of $dv(t)$ and $di(t)$, respectively, and $Z(jw)$ is the harmonic impedance of the network.

In digital applications, the transient signals within a window of length T_1 are sampled at an interval of ΔT. Discrete signals $dv[k\Delta T]$ and $di[k\Delta T]$ are obtained. The following equation is obtained through the discrete Fourier transform (DFT)

$$dV[jnw_1] = Z[jnw_1]dI[jnw_1] \quad (3)$$

Where $w_1 = 2\pi/T_1$, $dV[jnw_1]$ and $dI[jnw_1]$ are the DFT of $dv[k\Delta T]$ and $di[k\Delta T]$, respectively, and $Z[jnw_1]$ is the network harmonic impedance at frequency $nw_1/(2\pi)$.

Equation (3) implies impedance that the harmonic impedance of a network can be measured by using the DFT of the transient voltage and current signals. The following details should be noted

1. The transient signals in (2) and (3) are caused by an external disturbance instead of state changes in the network itself. The steady states of the network remain unchanged before and after the transients.
2. The transient process is completed within the sampling window of T_1 length.
3. Anti-aliasing filters are required before sampling if the frequency renge of the transcient signals exceeds $0.5\Delta T^{-1}$.

This uses a novel devices to create transient signals and measure the harmonic impedance. A complete scheme, including signal generation, signal acquisition and impedance calculation is devised and is introduced below.

2.2. Impedance Measurement Scheme in Single Phase Systems

In this method the device used adopts a waveform distortion technique, which was originally designed for power line communication or for computation purposes, to create the transient signals. Fig. 2 illustrates this model for the measurement of a LV system. A thyristor in series with a small inductor is connected between the driving point and the ground, and is identified as the signal generator (SG). The thyristor is turned on at a certain degree (denoted as the firing-angle) before the driving point voltage crosses zero, creating a temporary fault. This results in a thyristor current pulse flowing from the system. This current firstly increases and then decreases after the driving point voltage reverses its direction. As the current reaches zero, the thyristor shuts off automatically. Due to this turn off and on process thyristor draws nonlinear current from the system which in turn show up transient signal on the driving point voltage and line current waveforms and are used for impedance measurement.

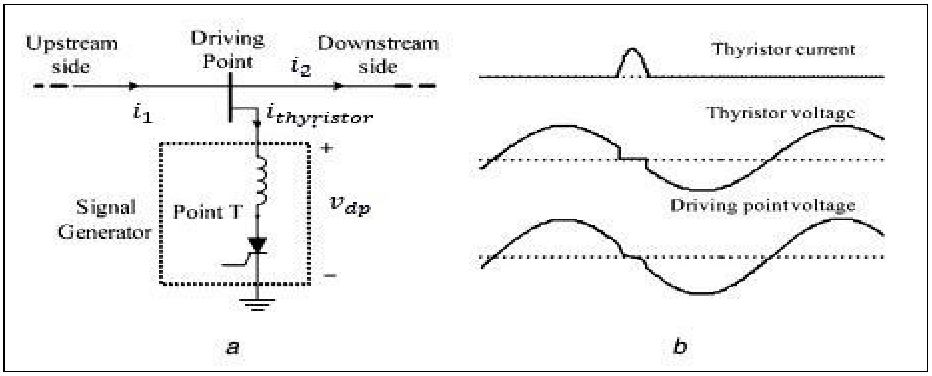


Figure 2: Illustration of the measurement method

a) Transient signal generation
b) Waveform containing transients

The inductor is used to limit the level the voltage distortions at the driving point. By adjusting the thyristor firing angle and using a proper inductor, the generated transient signals can be controlled in a negligible range. The same method can be used to check the variation harmonic impedance due to different FACTS devices.

The major problem in transient signal acquisition is, how to extract the transient signals from the recorded voltage and current waveforms. In this paper the extraction done by subtracting two consecutive cycles of a waveform. According to test results, the generated transient signal dies out with in one cycle [9]. The thyristors are fired so that a transient signal exists in only one of consecutive cycles. Therefore the difference two consecutive cycles is the transient signal

2.2.1. Measurement Algorithm

The DFT is performed for the extracted transient signals. $dV_{dp}, dI_{thyristor}, dI_1$ and dI_2 represent the DFT of the voltage transient at the driving point, the DFT of the thyristor current $i_{thyristor}$, the DFT of the upstream transient current, and the DFT of the downstream transient current, respectively. The supply system harmonic impedance Z_s, the driving point impedance Z_{dp} and the load impedance Z_{load} can be calculated as follows

$$Z_f(f) = -\frac{dV_{dp}(f)}{dI_1(f)}$$

$$Z_{dp}(f) = -\frac{dV_{dp}(f)}{dI_{thyristor}(f)}$$

$$Z_{load}(f) = \frac{dV_{dp}(f)}{dI_2(f)}$$

2.3. Measurement Scheme for Three-Phase Systems

This measurement is given as an example of measurement in multi-phase systems. In this case, the SG can be installed at multiple locations to create transient events using different channels. For example, it can be connected between phase A and the ground (denoted as the A-G channel), B and the ground and C and the ground. Phase-to-phase channels if A-B, B-C, C-B are also avalible. The multiple transient events need to be created in a short time in order to minimize the system variations during the measurement interval. The firing channels can switched manually, or automatically by using several thyristors. An automatic scheme uses four thyristors, with three them connected between each phase and a common point and the ground.

After multiple events are created and recorded, the following equations set is constructed at different frequency f where $Z_{aa}(f)$ phase self-impedance at frequency f; $Z_{ab}(f)$ and $Z_{ac}(f)$ are mutual impedances between phases A and B, and phases A and C, respectively; $dI_{am}(f)$ and $dV_{am}(f)$ are the DFT of phase A current and voltage transient signals of event m at frequency f; m is the number of events, and $m \geq 3$.

$$\begin{bmatrix} dI_{a1}(f) & dI_{b1}(f) & dI_{c1}(f) \\ \vdots & \vdots & \vdots \\ dI_{am}(f) & dI_{bm}(f) & dI_{cm}(f) \end{bmatrix} \begin{bmatrix} Z_{aa}(f) \\ Z_{ab}(f) \\ Z_{ac}(f) \end{bmatrix} = \begin{bmatrix} dV_{a1}(f) \\ \vdots \\ dV_{am}(f) \end{bmatrix}$$

Or

$$[dI(f)]_{m*3}[Z_a(f)]_{3*1} = [dV_a(f)]_{m*1}$$

The harmonic impedance measurement is completed by calculating the solution at different frequencies.

3. Basic Description of Facts Devices

3.1. Static Var Compensator

Static var systems are used in power system for rapid control of voltage at weak point in a network. Static var compensator (SVC) are shunt connected static generator/absorber whose outputs can be varied to control voltage in power system. Even though SVC uses in power system to provide high performance in steady state and transient voltage stability control, to damp power oscillations, to reduce system loss and to control real and reactive power flows it is thyristor based non-linear device. It introduces transients into the system at point where it is connected. Here FC-TCR type SVC is taken into account and model is shown in Fig. 3

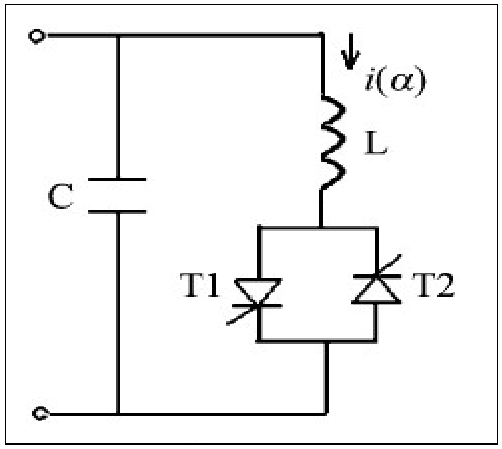


Figure 3: Fixed Capacitor Thyristor Controlled Rectifier

3.2. Thyristor Controlled Series Capacitor (TCSC)

Thyristor controlled series capacitor is series compensated FACTS device which consists series capacitor bank shunted by a thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance. Fig. 4 shows a single line diagram off TCSC controller. The TCSC is a variable thyristor controlled reactor which is connected across a series capacitor.

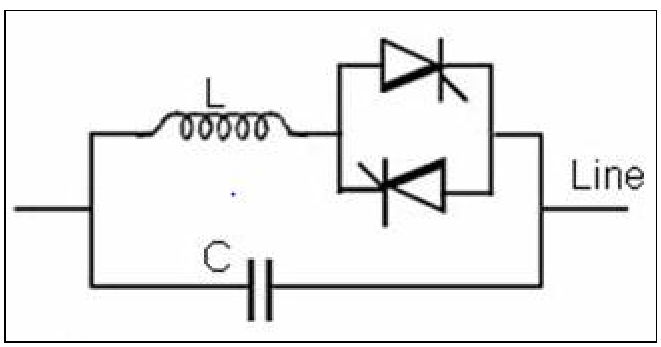


Figure 4: Thyristor Controlled Series Capacitor (TCSC)

3.3. Static Synchronous Series Compensator (SSSC)

SSSC is the one of the most important FACTS controllers. It is like a STATCOM except that the output ac voltage is in series with the line. It can be based on voltage source converter or current source inverter. SSSC can only inject variable voltage, which is 90 degrees leading or lagging the current. Fig. 5 shows the block diagram of SSSC.

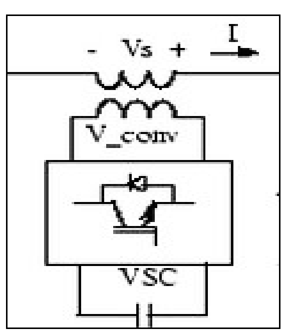


Figure 5: Simple block diagram of Static Synchronous Series Compensator (SSSC)

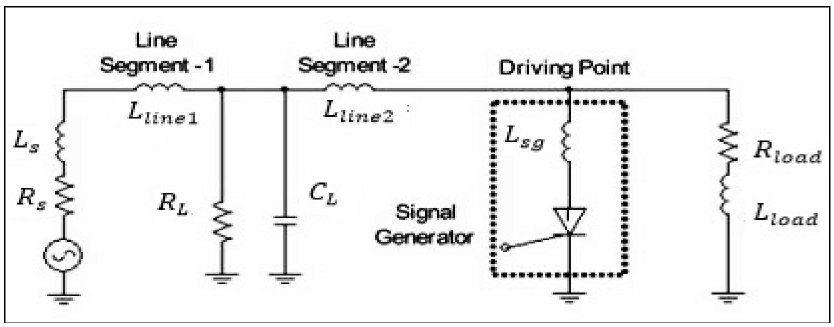
This devices generates controllable transients by adjusting the firing-angle so that enough strength is available for accurate measurement independent of the condition at different locations. As well, the impact of the transients on system operation is maintained in an acceptable range. The SG device is simple and inexpensive since it requires no power electronic component with gate-turn-off ability. It can be constructed as a portable device for measuring LV systems. This measurement scheme is immune to background harmonics.

4. Computer Simulation

Computer simulations were performed to test the above measurement scheme, and the result are presented in this section.

4.1. Simulation in a Single-Phase LV System

Simulation was done in a customer-level 120 V 60 HZ single-phase system as shown in Fig. 6. Transients created by SG using different firing angles. The waveforms of driving voltage, the transient on the driving point voltage are plotted in Fig. 7, which shows the transients caused by the FACTS devices. The distortions on the waveform of the driving point voltage are unnoticeable with the naked eye, and the peak distortions was very small. Therefore the influence of the SG firing on the load operation can be ignored. A DFT was performed for the transient signals.



$R_s = 0.06\ ohms, L_s = 0.08mH, L_{line1} = 0.01M, L_{line2} = 0.02mH, R_L = R_{load} = 7.2ohms,$

$C_L = 178.43\mu F, L_{sg} = 0.2mH, L_{load} = 9.2mH$

Figure 6: The 120V single-phase simulation system and its response during SG firing

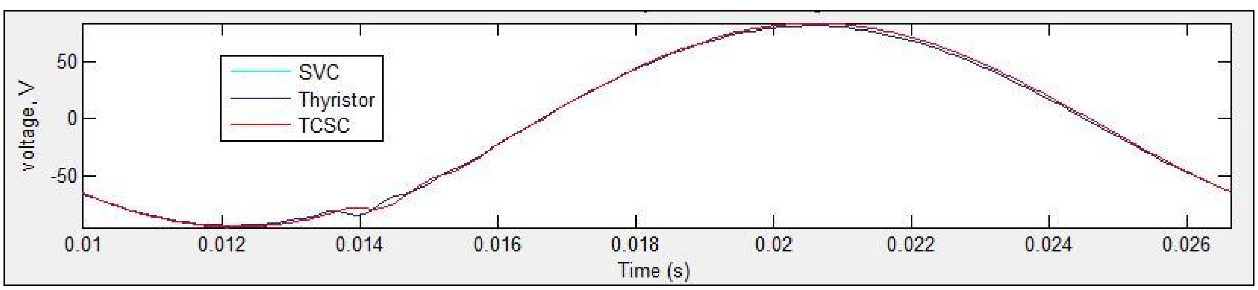


Figure 7: The driving point voltage transients for shunt and series controllers

Fig. 8 present the simulation results of harmonic impedance of single phase LV network of Fig 6. Which shows the variation of harmonic impedance for series and shunt FACTS controllers.

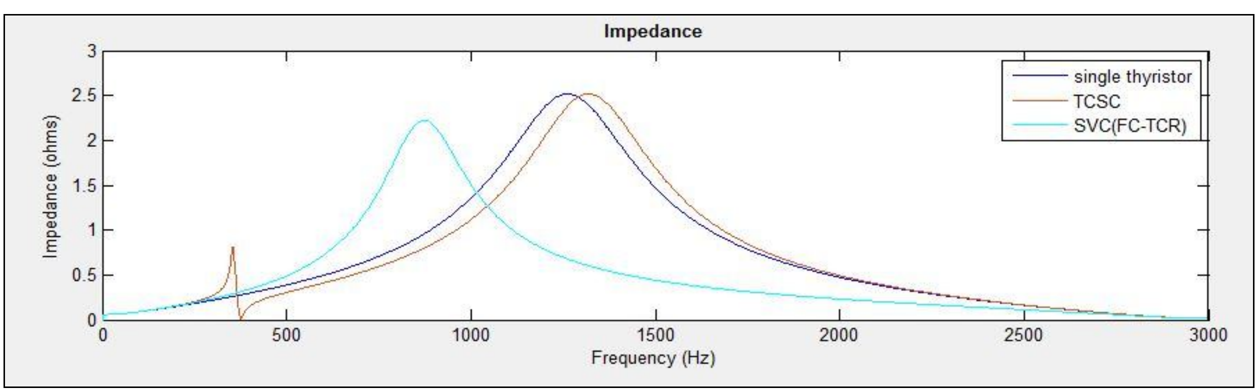


Figure 8: Change in Harmonic impedances of network due to single Thyristor, TCSC and SVC.

We can clearly say from the above simulations that how the resonance frequency is varying from device to device. TCSC shows more distortion in impedance value when compared to other devices. Which means that series connected devise caused more deviations in the power system impedance. This is due to the presence of extra thyristor and inductance elements in the network which is nothing but presence of non-linear elements in the network. Furthermore this variations are can be controlled by varying the firing angles if the thyristors, so that load impedance is much larger than the system impedance at high frequencies.

4.2. Simulation in a Three-Phase System

Simulations were also carried out in 25kV 60Hz distribution system (Fig. 8) to know the effect of FACTS devices in this system. System has phase coupled segment-1 and 2 and a three phase transformer. Transient events are created by using different FACTS devices with bigger firing angles when compared to 120V system in order to achieve enough signal strength.

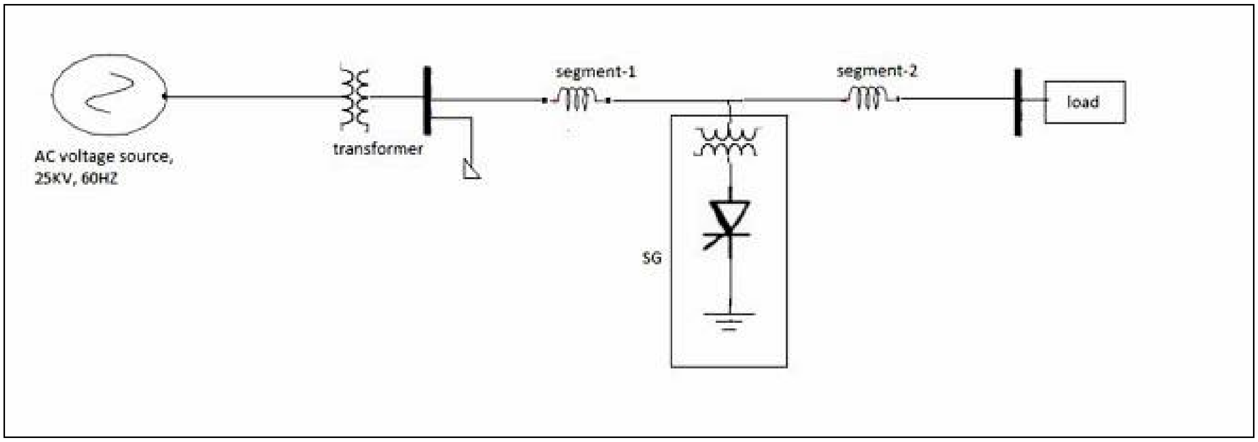


Figure 9: Single line diagram of 25kV 60Hz 3-phase distribution system

Fig. 10 shows the measured harmonic impedance of the three phase distribution system for different FACTS devices. From this measurement we can say that series FACTS controller has significant effect on harmonic impedance of the network when compared to the shunt controllers.

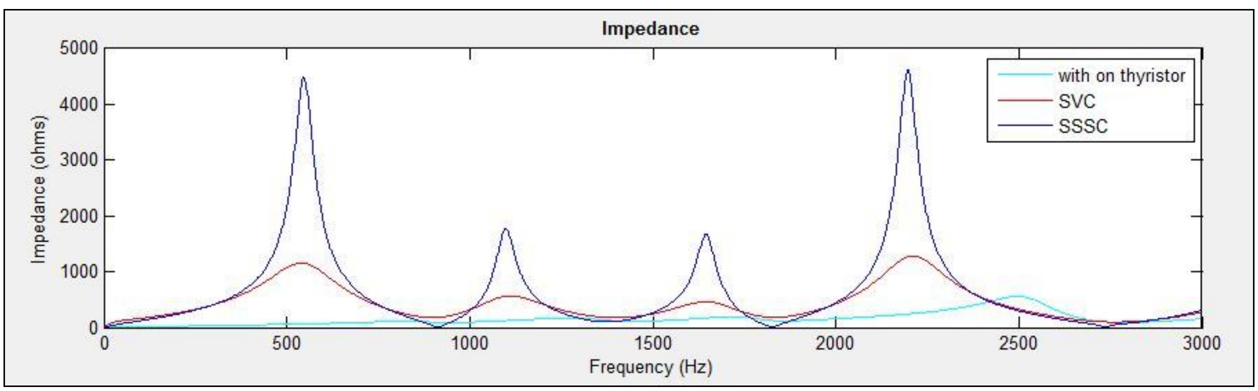


Figure 10: Measurement results for the 2kkV 3-phase system

In practical applications, transients can be created by using multiple firing angles and a proper combination of multiple firing angles and a proper combination of multiple channels to obtain reliable results.

5. Conclusions

Effect of different FACTS devices on harmonic impedance on a LV network are presented in this paper. The method used for this measurement is a very effective and easy method for measurement of harmonic impedance. It utilizes a device (FACTS) to create a controlled short circuit at the driving point. Transient current and voltage signals are generated and used for harmonic impedance measurement. The strength of transient signals is adjusted through thyristor firing angle, so that accurate measurements are supplied and the disturbances to the load operation are negligible. This method can be easily implemented in a low-cost and portable devices. And the results of the analysis can be summarized as, Static Var Compensator has significant effect on the system impedance value than the thyristor due to the presence of extra thyristors and inductive elements. SSSC has a most significant effect on the impedance when compare to any other shunt and series FACTS controllers.

This analysis can be used as a guideline for low voltage harmonic analysis and can used to design harmonic filters. Choosing appropriate filter design for different FACTS controllers in LV networks.

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