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MATLAB Simulation of Variable Frequency Transformer for Power Transfer in-between Power System Networks

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Abstract

During mid 2000's a variable frequency transformer (VFT) was used successfully as efficient AC link between two power system networks. This new technique didn't use both High-Voltage Direct Current (HVDC) link and Flexible AC Transmission System (FACTS) i.e., power electronics converter-based power transmission control system. In fundamental nature, VFT is a rotating transformer which facilitates torque and speed adjustments to control the power transmission. This paper presents a MATLAB simulated model of VFT used as a controllable bidirectional power transmission machine for controlling the power flow between two power system networks. Using MATLAB, simulation model of VFT is developed and several analysis are done regarding the ease of power transmission and its controllability. The results from analysis under load switching condition are presented in this paper. The torque, speed, voltage, active power flow and THD analysis results are graphically visualized. Based on these simulation results, the use of VFT for power transmission and its controllability is justified over the conventional HVDC and FACTS technologies.

Keywords

Power transmission, Interconnection, Flexible ac link, MATLAB simulation, Variable Frequency Network

1. Introduction

Electric power supply systems are widely interconnected. The geographical disparity between load centers and the generation forces us to go for grid interconnections. This is basically used to reduce the economic cost and for the improvement of the reliability of the system [1]. Conventional grid interconnections systems solutions include ac interconnection, just interconnection of two synchronous systems with ac transmission lines and back-to-back HVDC, asynchronous interconnection which is implemented via HVDC [2]. AC transmission is simple as well as economic but it arises the stability problems on certain severe faults and the increases the complexity of the system. The process is step-wise (one at time) and slow (to deal with the stability). In case of HVDC, it is easier for transfer of bulk power and also flexible for the system. But the design of HVDC is quite complicated as well as expensive as the HVDC require converter plant at the sending end and the inverter plant at the receiving end of the system. Growing technological advancement came with new technique which could minimize above problems known as Variable Frequency Transformer (VFT). The first VFT in the world, the Langlois Substation in Québec, Canada, was put into operation in October 2003 to interconnect with the grid in New York [3].

2. VFT Concept and components

Simply, VFT is the doubly fed wound rotor induction machine (WRIM), which includes a rotary transformer, a DC drive motor, and a collector ring which as a system acts as the bidirectional transmission device and can transfer power in-between the power system networks. The VFT has a stator and a rotor which are magnetically coupled and is provided with the three phase windings. One power system is connected to stator side and another side is connected to rotor side. The rotor is made similar to stator and wound for the same number of poles [4]. A stable power is exchanged between two power system networks by simply controlling the speed and torque applied to the rotor by magnetically coupled DC motor drive. Thus, the magnitude and direction of flow being proportional to the magnitude and direction of torque applied. The electrical power is transferred in between the networks by magnetic coupling through the air gap of the VFT and both are electrically isolated.

During synchronism between two networks, the rotor of the VFT maintains the position at which the stator and the rotor voltage are in phase with the associated systems. To transfer the power from one system to the other torque is applied in a specific direction and when applied to opposite direction the power get transferred in reverse direction. This power transmission is proportional to the magnitude and direction of the torque applied. The drive motor is designed to provide torque even at standstill condition. As the two systems are out of synchronism, the rotor of the VFT will rotate continuously and the rotational speed will be proportional to the difference in frequency of the systems. The rotors inherently orient itself to compensate the phase angle difference assessed by the two asynchronous systems [5].

3. VFT Model and Analysis

3.1 VFT Model

In this paper, the model presented consists of doubly-fed wound rotor induction machine with three phase windings provide on both stator side and rotor side. The two power systems are connected through the VFT as shown in Fig.1. The power system #1 is connected to the stator side, energized by voltage V_S with phase angle, θ_S while the rotor side is connected to power system #2 energized by voltage V_R with phase angle, θ_R. The DC drive motor is mechanically coupled to the rotor the WRIM along with control system to apply torque, T_D. So the applied torque adjusts the position of the rotor relative to the stator, thereby controlling the direction of the magnitude of power flow through VFT [6]. During the whole analysis in this paper, only real power transmission is being discussed.

3.2 VFT Analysis

The power transmission through the VFT can be simplified in mathematical form as:

$$P_{VFT} = P_{MAX} Sin\theta_{net} \quad (1)$$

where,
P_{VFT} = Power transmission through VFT from stator to rotor,
P_{MAX} = Maximum theoretical power transmission possible through the VFT in either direction which occurs when the net angle θ_{net} is near 90^0.
The P_{MAX} is given by:

$$P_{MAX} = V_S V_R / X_{SR} \quad (2)$$

where,
V_S = Voltage magnitude on stator terminal,
V_R = Voltage magnitude on rotor terminal and
X_{SR} = Total reactance between stator and rotor terminals.
Also,

$$\theta_{net} = \theta_S - (\theta_R + \theta_{RS}) \quad (3)$$

where,
θ_S = Phase-angle of ac voltage on stator, with respect to a reference phasor
θ_R = Phase-angle of ac voltage on rotor, with respect to a reference phasor and
θ_{RS} = Phase-angle of the machine rotor with respect to stator.

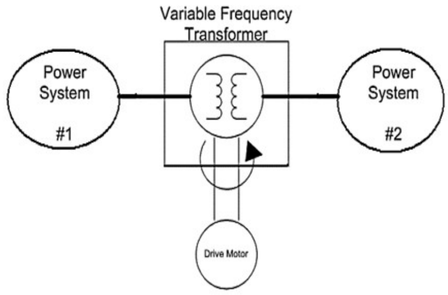

Figure 1: The VFT model representation

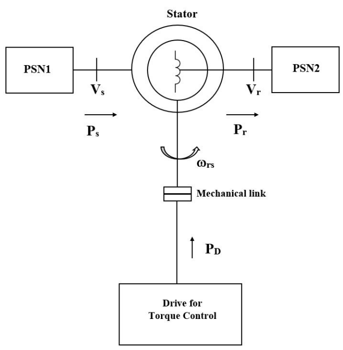

Figure 2: Power transmission from PSN 1 to PSN 2 using VFT

Therefore, the power transmission through the VFT is given by:

$$P_{VFT} = \frac{V_S V_R}{X_{SR}} sin(\theta_s - (\theta_R + \theta_{RS})) \quad (4)$$

Phasor diagram for above mathematical relation is illustrated below in Fig.3.

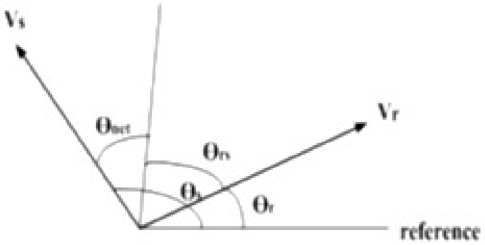

Figure 3: Phasor Diagram for VFT

To ensure the stable operation of the VFT, the angle θ_{net} must have the value significantly less than 90^0. The power transmission will be constrained to a fraction of the maximum theoretical level given in (2). Here, the power transmission equations are analyzed based on assumption that VFT is an ideal and lossless machine, with negligible leakage reactance and magnetizing current. The power balance equation requires that the electrical power flowing out of the stator winding must flow into the combined electrical path on the rotor winding and the mechanical path to the drive system, i.e.

$$P_S = P_D + P_R \tag{5}$$

where,
P_S = electrical power to the stator windings
P_D = electrical power to the rotor windings and
P_R = mechanical power from the torque control drive system.
We know the ampere turns in transformer must balance between both sides thus in VFT also the ampere turns balance between the rotor and stator side, i.e.

$$N_S I_S = N_R I_R \tag{6}$$

where,
N_S = number of turns on stator winding,
N_R = number of turns on rotor winding,
I_S = current out of the stator winding,
I_R = current out of the rotor winding

The magnetic flux linkage by both the stator and the rotor remains same but differ in terms of frequencies in such a way that voltage also differ by the same ratio.

$$V_S = N_S \times f_S \times \psi_a \tag{7}$$

$$V_R = N_R \times f_R \times \psi_a \tag{8}$$

$$\frac{V_R}{N_R} = \frac{V_S}{N_S} \times \frac{f_R}{f_S} \tag{9}$$

f_S = frequency of voltage on stator winding (Hz),
f_R = frequency of voltage on stator winding (Hz),
ψ_a = air-gap flux In fundamental nature, during the steady state, the rotor speed is proportional to the difference in the frequency on the stator and rotor windings,

$$f_{rm} = f_S - f_R \tag{10}$$

and

$$\omega_{rm} = f_{rm} \times 120/N_P \tag{11}$$

where,
f_{rm}= rotor mechanical speed in electrical frequency (Hz)
N_P = number of poles in the machine, and
ω_{rm} = rotor mechanical speed in rpm.
Assembling the above mentioned relationships, the power exchanged through the drive system is obtained as:

$$\begin{aligned} P_D &= P_S – P_R \\ &= V_S \times I_S – V_R \times I_R \\ &= V_S * I_S – (N_R * V_S/N_S * f_R/f_S) * (N_S * I_S/N_R) \\ Thus, P_D &= P_S \times (1 - f_R/f_S) \end{aligned} \tag{12}$$

The torque produced by the drive system (TD) is

$$\begin{aligned} T_D &= P_D/f_{rm} \\ &= V_S \times I_S \times [(f_S - f_R)/f_S]/(f_S - f_R) \\ &= V_S \times I_S/f_S \\ &= N_S \times f_S \times \psi_a \times I_S/f_S \\ T_D &= N_S \times f_S \times \psi_a \end{aligned} \tag{13}$$

From above analysis it can be understood that drive system torque, TD is independent of rotational speed rather only proportional to the stator current and air gap flux. As the VFT operates near constant flux, it indicates that torque is the function of stator current only. Thus, provided that stator frequency is constant, applied torque remains proportional to the power transmission through the VFT.

4. MATLAB Simulation Model

To create a Simulink simulation model of VFT, we represented it by a wound rotor induction machine with doubly fed condition. The WRIM is simulated using Asynchronous Machine SI units. The power system networks are simulated using three phase voltage sources and fed to the stator and rotor of machine. The torque is provided using the function created in the MATLAB. The loads are operated for certain intervals using load switching technique. For this, load switching of circuit breaker and signal builder are used.

Using the model in figure 9, power exchange analysis between rotor and stator side of the VFT was done under several load switching conditions.

5. MATLAB Simulation Results

5.1 Synchronous Mode of Operation:

(i.e. f1 =50 and f2 = 50)

5.1.1 Rotor Speed Curve:

Fig.4 is the plot of the rotor speed while operating in synchronous mode.

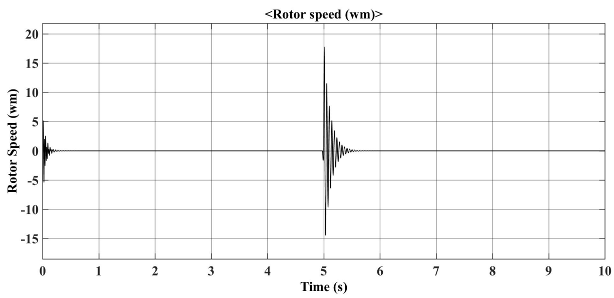

Figure 4: Speed Curve

5.1.2 Torque Curve:

Fig.5 is the plot of the torque generated by the controller while operating in synchronous mode.

5.1.3 Power flow Curve

Fig.6 is the plot for power flow from PSN 1 to PSN 2 where as Fig.7 is the plot for power flow from PSN 2 to PSN 1.

5.1.4 System Frequency

Fig.8 shows the plot of current which depicts that both the power system has the system frequency of 50Hz while operating in synchronous mode.

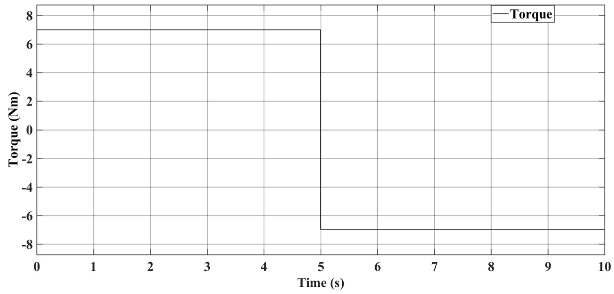

Figure 5: Torque Curve

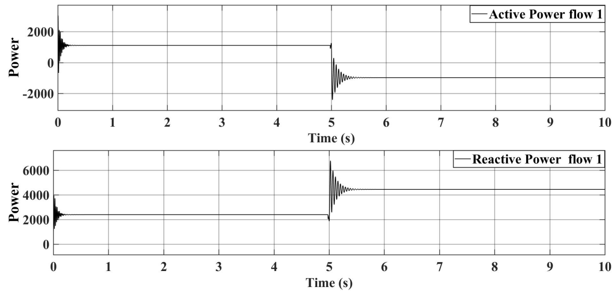

Figure 6: Power flow from PSN 1 to PSN 2

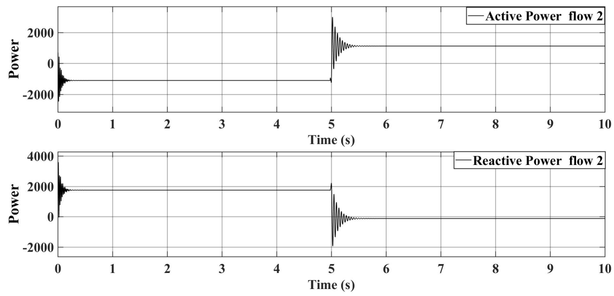

Figure 7: Power flow from PSN 2 to PSN 1

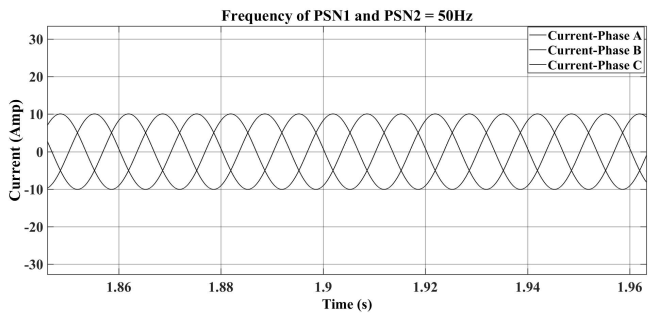

Figure 8: Frequency of power exchanged between PSN

5.1.5 Total Harmonic Distortion Analysis:

Fig.10 and Fig.11 show the THD calculation of PSN 1 and PSN 2 where it is 0% in both systems.

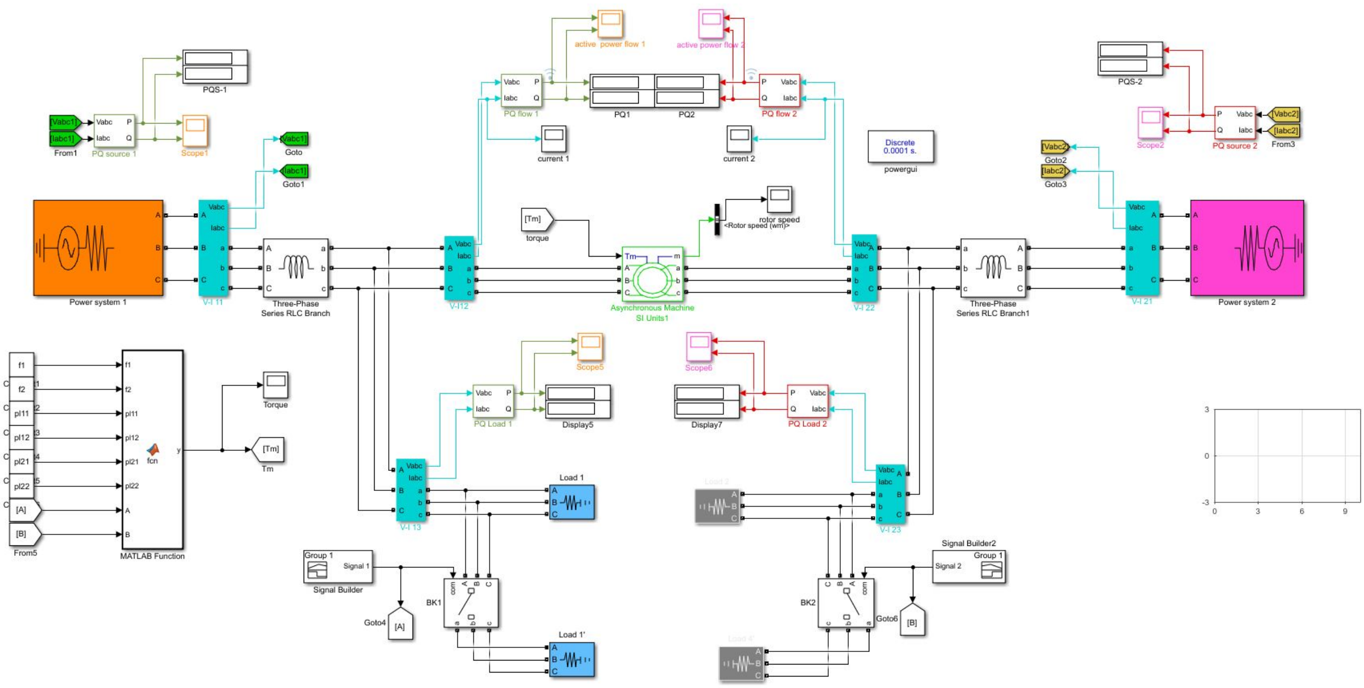

Figure 9: MATLAB Simulation model of VFT

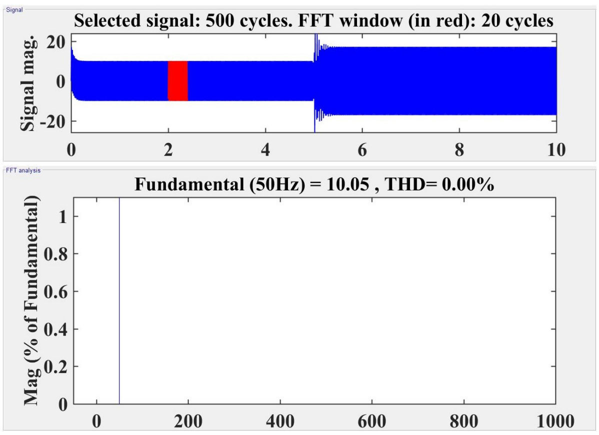

Figure 10: THD calculation of PSN 1

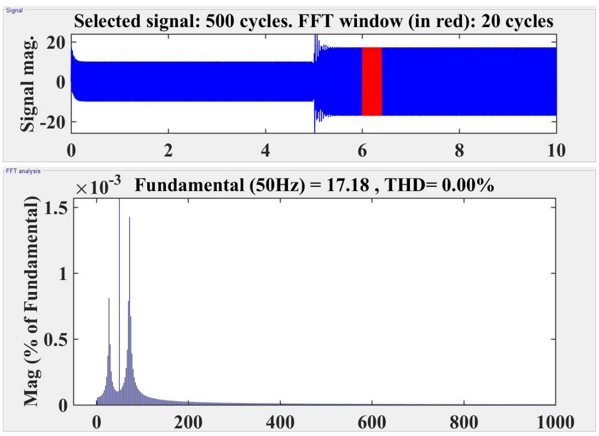

Figure 11: THD calculation of PSN 2

5.2 Asynchronous Mode of Operation:

(i.e. f1 =60 and f2 = 50)

5.2.1 Rotor Speed

Fig.12 is the plot of the rotor speed while operating in asynchronous mode.

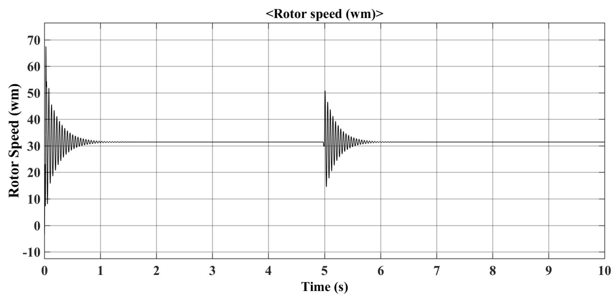

Figure 12: Rotor Speed

5.2.2 Torque Curve:

Fig.13 is the plot of the torque generated by the controller while operating in asynchronous mode.

5.2.3 Power flow Curve

Fig.14 is the plot for power flow from PSN 1 to PSN 2 where as Fig.15 is the plot for power flow from PSN 2 to PSN 1.

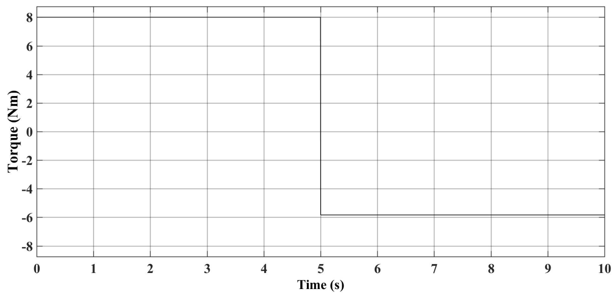

Figure 13: Torque Curve

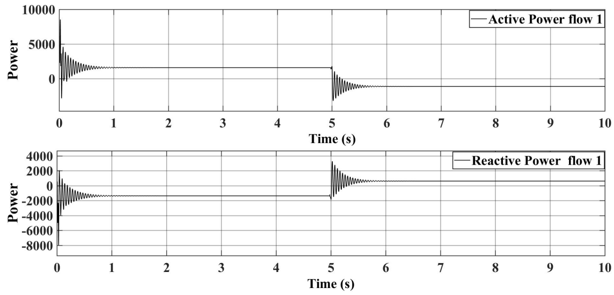

Figure 14: Power flow from PSN 1 to PSN 2

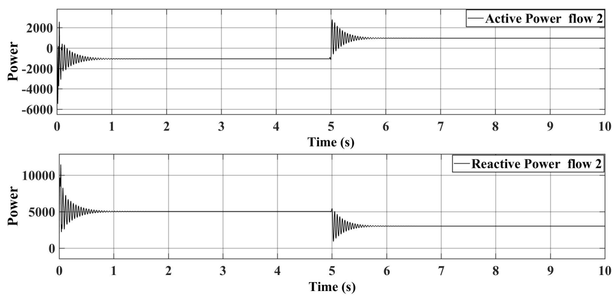

Figure 15: Power flow from PSN 2 to PSN 1

5.2.4 System Frequency

Fig.16 and Fig.17 show the plot of current which depicts that PSN 1 has system frequency of 60Hz and the PSN 2 has the system frequency of 50Hz while operating in asynchronous mode.

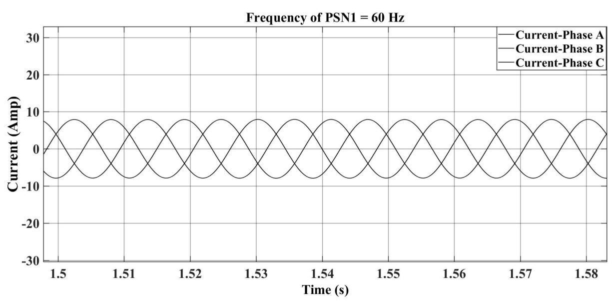

Figure 16: Frequency of power sent from PSN 1 to PSN 2

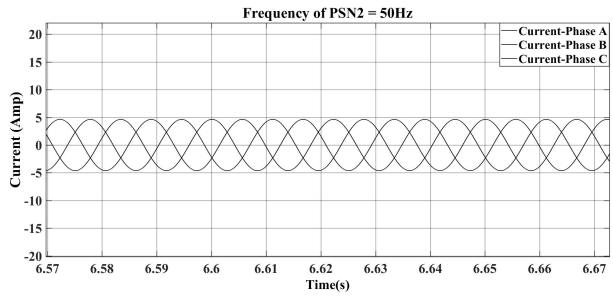

Figure 17: Frequency of power sent from PSN 2 to PSN 1

5.2.5 Total Harmonic Distortion Analysis:

Fig.18 and Fig.19 show the THD calculation of PSN 1 and PSN 2 where it is less than 3% in both systems.

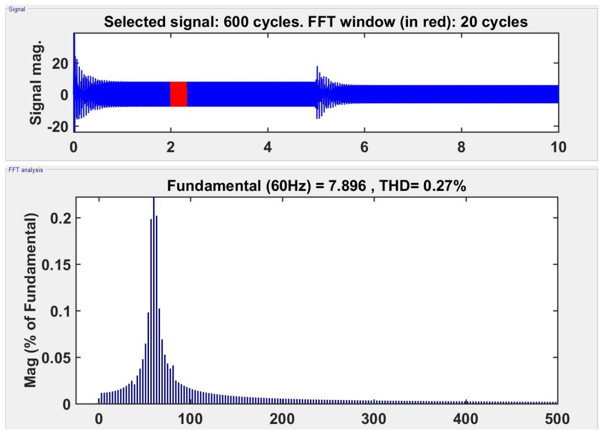

Figure 18: THD calculation of PSN 1

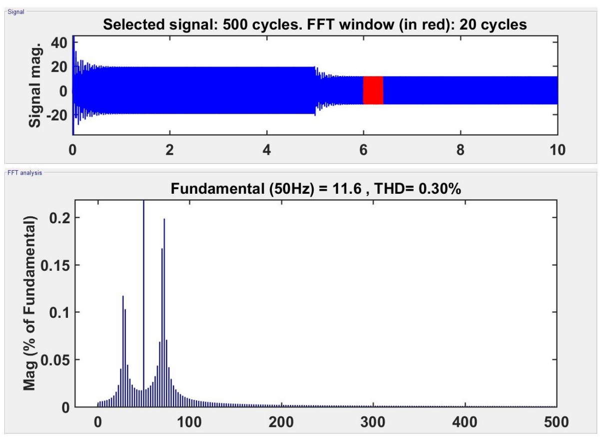

Figure 19: THD calculation of PSN 2

6. Conclusions

From the various results obtained it is evident that power can be transmitted through VFT bidirectionally in between power systems which is directly proportional to the applied torque. VFT provides an option for achieving the real power transmission or power flow control in between two or more power systems. The direction and magnitude of power transmission control are achieved. The speed, torque, power flow and current plots are also obtained and THD is calculated. Thus, the VFT concept discussed and its advantages are verified by simulation results. It has distinct advantage in terms of controllability over conventional phase angle regulating transformer and doesn't inherently produce harmonics in case of many HVDC and FACTS technology.

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