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Stability analysis and efficiency improvement of IPFC using latest PR controller

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Abstract: The deviation from the ideal waveform causes disturbances and failure of end-user load equipment. Power traveling a long distance from the generation plant to the end-user leads to deterioration of its quality, and the intensive utilization of power leads to serious issues in the grid resulting in power quality problems. To make the system effective and able to meet modern requirements, flexible AC transmission system (FACTS) devices should be installed into the grid. The interline power flow controller (IPFC) is the latest FACTS device, which compensates for both active and reactive power among multi-line systems. The converters used in the IPFC are crucial as they can be adjusted to regulate the power flow among the lines. This paper proposes a cascaded IPFC with hysteresis and proportional resonant voltage controllers. Some main drawbacks of controllers like steady-state errors and reference tracking of converters can be easily achieved by the PR controller, which makes the system efficient and can be used for a wide range of grid applications. Hysteresis and PR controllers are explained in detail in the following sections. A comparative analysis is carried out among control algorithms to choose the suitable controller which maintains stability in the system.

Key words: control algorithms, FACTS devices, interline power flow controller, multilevel inverter

1. Introduction

The modern world is based on electricity. It plays a major role in the modern world. With the development of technology, the requirement for power has increased. In the past centuries, we mainly depended on the energy generated from coal, petroleum, natural gas, but this led to great pollution problems [1–3]. Therefore, the modern world pays attention to renewable energy and distribution energy sources. During the last few years, most of the research has focused on grid integration i.e. the integration of renewable energy sources with the grid. The aim of this is to ensure that the integration of these sources does not affect the operation of the power system with respect to reliability, security and power quality [4, 5].

The inverter is used for connecting these renewable sources with the utility grid. The grid connected inverter has been a major point of research as it should control the unbalanced voltage or current, improve the power factor, harmonic compensation and compensate the unbalanced and distorted non-sinusoidal voltage into the grid [6, 7] and due to many other environmental effects on grid there have been many PQ (power quality) problems like voltage swag, voltage swell and harmonics. FACTS (Flexible AC Transmission System) devices have become a solution for many of such causes. The FACTS enhance the controllability and increases power transfer capability of the electric transmission network [8, 9]. FACTS devices improve transmission quality and reliability of the network. They reduce the power delivery costs and improve the efficiency of the network. They are classified into series compensation and shunt compensation.

The series compensation is used to improve the performance of Extra High Voltage (EHV) lines. Here, the capacitor is connected in series with the network wherever necessary. This increases the transmission capacity and improves the system stability.

When a new line is to be added or an existing circuit is to be adjusted in order to strengthen the system and maximize power transfer or minimize losses, the series compensation can be used. The main function of these devices is to control power flow in transmission lines, transient stability and voltage control and many more. Among these, the IPFC (interline power flow controller) has become a major point of research these days due to its capability of simultaneous control of multi-line systems. The IPFC is a series compensation for a FACTS device.

Along with the sophisticated electrical and electronic technology and usage of high-power devices, the utility of power has drastically increased in various ways. This shows its impact on the transmission system.

Harmonic regulation is crucial on the transmission side because of the harmonic effect of the load on the transmission system. In order to regulate harmonics, various control techniques [10,11] are used but these control techniques have some limitations, they are unable to compensate for the complete voltage sag, require ultra-capacitors at the DC link, require active power during compensation, high DC link rating [12]. Harmonics are mostly caused by nonlinear loads on the system and these frequencies are the cause for power quality problems. Power converters are playing a key role in feeding electrical loads by controlling and converting the ac power. These converters and nonlinear loads on the system are the major reasons of power pollution and lead to power quality problems [13, 14]. Current harmonics causes voltage harmonics. Source voltage gets distorted due to current harmonics. So, small source impudence results in lower voltage harmonics. In the case of nonlinear loads special design considerations are to be made because current in the system increases with the effect of harmonics and this affects the electrical equipment.

In this paper new controllers are proposed, namely hysteresis and PR. Here, a comparative study is carried out between hysteresis and PR controllers for regulating harmonics and maintaining stability in transmission systems, to choose which controller will be appropriate for maintaining the stability.

2. Interline power flow controller

The IPFC is the latest FACTS controller and the most advanced controller. It consists of two voltage-controlled sources connected back-to-back and having a DC link in common.

The IPFC is a series compensating device which means it employs an inverter to each line for series compensation. In other words, static synchronous series compensators play a key role in power transmission through lines they are connected to. The scheme of the IPFC is shown in Figure 1, both compensating inverters are connected together at their DC terminals. This structure enables the supply of real power from its own line to the DC link to be controlled by the inverter in addition to series reactive compensation. The surplus power of underutilized lines is used for real power compensation in other lines. This way, overloaded lines are equipped with real and reactive power control capable devices similar to a unified power flow controller (UPFC). This general principle helps in real power transfer from over-loaded lines to under-loaded lines, the power balance at the common DC link must be mandatory through a proper control action.

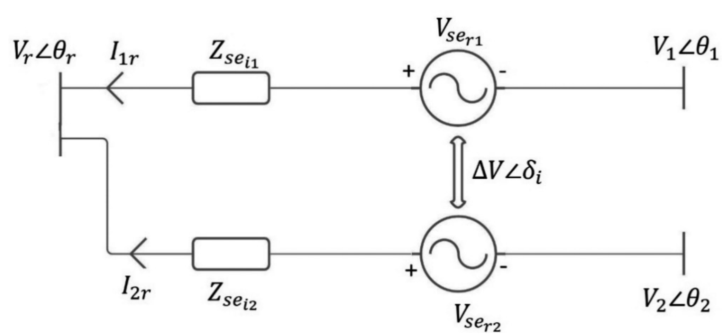


Fig. 1. IPFC power injection model

IPFC rating is specified by voltage-current rating and the injected maximum voltage. When the rated value of the line current, which depends on the power transferred through the line, and the injected voltage are equal, only then the IPFC reaches its rated power.

Active power through the DC link should be maintained at zero in order to maintain constant DC bus voltage. Equation (1) shows the injected active power to the line. Equation (2) is the active power flow constraint through the DC bus. V_s, V_r are the voltage magnitudes at two ends of lines and similarly θ_s, θ_r are the phase angles. δ_i is the phase angle of the injected voltage ΔV.

To maintain constant DC voltage, active power through the DC link must be zero. this is achieved when the power injected into one line is equal to the active power supplied by another line.

Equation (1) gives the relation between injected/absorbed active power and the angle of the series device.

$$P_{se_i} = \left(\Delta V_i \cdot V_s \cos(\delta_i) + \Delta V_i^2 - \Delta V_i \cdot V_{ir} \cdot \cos(\delta_i - \theta_{ir})\right) G_i + (\Delta V_i \cdot V_s \sin(\delta_i) - \Delta V_i \cdot V_{ir} \cdot \sin(\delta_i - \theta_{ir})) B_i, \tag{1}$$

$$P_{se_1} + P_{se_2} = 0, \tag{2}$$

$$\delta_{i\,\max P} = a\tan\left(\frac{V_{ir} \cdot G_i \cdot \sin(\theta_{ir}) - V_s \cdot B_i + V_{ir} \cdot B_i \cdot \cos(\theta_{ir})}{-V_s \cdot G_i + V_{ir} \cdot G_i \cdot \cos(\theta_{ir}) - V_{ir} \cdot B_i \cdot \cos(\theta_{ir})}\right). \tag{3}$$

V_r, V_1, V_2 are the complex bus voltages at the busses r, 1, 2, respectively. They are defined as $V_i = V_i \angle \theta_i$ $(i = r, 1, 2)$. $V_{se_{rn}}$ is the complex, controllable, series injected voltage source, defined as $V_{se_{rn}} = V_{se_{rn}} \angle \theta_{se_{rn}}$ where $n = (1, 2)$. The impedance of the series injection transformer is represented by $Z_{se_{rn}}$.

The power injections at busses, after neglecting the resistance of the series coupling transformer and transmission lines are summarized as:

$$P_{inj,r} = \sum_{n=1,2} V_r V_{se_{rn}} b_{rn} \sin(\theta_r - \theta_{se_{rn}}), \tag{4}$$

$$Q_{inj,r} = -\sum_{n=1,2} V_r V_{se_{rn}} b_{rn} \cos(\theta_r - \theta_{se_{rn}}), \tag{5}$$

$$P_{inj,n} = -V_n V_{se_{rn}} b_{rn} \sin(\theta_n - \theta_{se_{rn}}), \tag{6}$$

$$Q_{inj,n} = V_n V_{se_{rn}} b_{rn} \cos(\theta_n - \theta_{se_{rn}}). \tag{7}$$

The active power exchange via the DC link and between the converters is zero, as it neither absorbs nor injects power, with respect to the ac system.

$$\mathrm{Re}\left(V_{se_{r1}} I_{1r}^* + V_{se_{r2}} I_{2r}^*\right) = 0. \tag{8}$$

In Equation (8), $*$ indicates the conjugate of complex power. The above equation, neglecting the resistance of the series injection transformer is written as:

$$\sum_{m=r,1,2} P_{inj,m} = 0. \tag{9}$$

As the IPFC is a multi-line system, it controls the power flow among the lines, where it is placed. The constraints of power flow are described by the below equations.

$$P_{nr} - P_{ri}^{\text{spec}} = 0, \tag{10}$$

$$Q_{nr} - Q_{nr}^{\text{spec}} = 0. \tag{11}$$

$P_{ri}^{\text{spec}}, Q_{nr}^{\text{spec}}$ are the specified active and reactive power flow control references and

$$P_{rn} = \text{Re}\left(V_n I_{nr}^*\right), \tag{12}$$

$$Q_{rn} = \text{Im}\left(V_n I_{nr}^*\right). \tag{13}$$

Thus, the equations of power balance are given as:

$$P_{\text{gen},m} + P_{inj,m} - P_{rm} - P_{\text{line},m} = 0, \tag{14}$$

$$Q_{\text{gen},m} + Q_{inj,m} - Q_{rm} - Q_{\text{line},m} = 0. \tag{15}$$

$P_{\text{gen},m}$, $Q_{\text{gen},m}$ represent the generation, P_{rm}, Q_{rm} are the load active and reactive powers.

3. Inverter

Converting DC input to AC output is the primary function of inverters. The obtained output can be constant or can have variable amplitude and frequency. Due to the nonlinear behavior of electric machines and semi-conductor devices used in inverters, harmonics are generated. However, the harmonic content can be reduced by implementing proper control techniques and high-speed semi-conductor devices. Nearly sinusoidal output is generated from DC input using a multilevel inverter. In high-voltage and power applications multi-level inverters are playing a key role due to their advantages like generating higher voltages using lower rating devices [15] and with increased levels better voltage outputs are generated with reduced total harmonic distortions [16, 17]. There are different topologies depending on their features like control flexibility, modularity, the number of switches and their requirements, etc. Based on the application requirement, an appropriate topology is employed. With the number of increases in switches, the losses increase, protection circuits and gate driver units are to be added. In order to evaluate the characteristics of the inverter, total standing voltage (TSV) (total voltage blocking) is one of the main criteria.

The cascaded multi-level inverter is the series combination of a single full-bridge inverter, each having its own DC bus. Each level of four switches in different combinations with DC input and AC output generates five (+2Vdc, +Vdc, 0, –Vdc, –2Vdc) different voltage outputs. The output of an M-level inverter is the output combination of all individual inverters. In order to achieve medium voltage with low harmonics, H-bridge cells are connected in parallel on the AC side.

In three-phase systems, three identical single-phase cascaded inverter outputs are connected in either delta or star configuration.

4. Control techniques

To control the inverter, various PWM techniques are implemented [18]. Control algorithms play a crucial role in controlling the output voltage of the system. They control by generating switching signals for inverter switches [19]. There are many control algorithms like sinusoidal pulse width modulation (SPWM) as well as space vector modulation (SVM) [20] and many more, which are classified according to different criteria [21]. A suitable controller is to be selected in order to overcome the grid disturbances and uncertainties. Researchers are coming out with various advanced control techniques [22].

The most fundamental controllers are proportional (P), proportional derivative (PD), proportional integration (PI) and proportional integral derivative (PID). They are considered as the base of the control theory [23–26].

To obtain zero steady-state error [27] the proportional integral (PI) controller is used. However, its drawbacks are due to poor integral performance action. Its capability of disturbance rejection is poor and cannot track sinusoidal reference without the steady-state error.

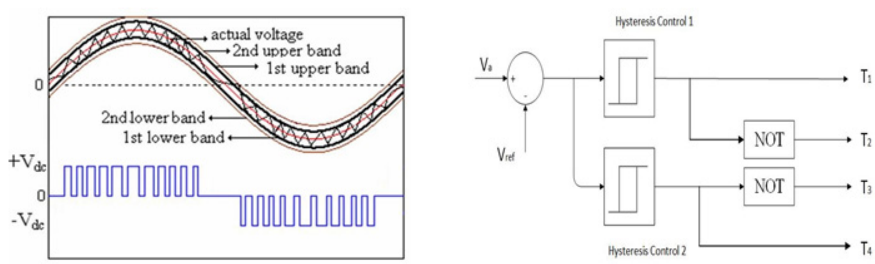
Hysteresis control is a nonlinear method of control [28–31]. Here, based on the reference tracking, gating signals are generated because these controllers track errors between measured and reference voltages. This is described briefly in the following sections.

4.1. Hysteresis controller

The hysteresis controller needs two voltage signals, one is the source voltage and the other is the voltage being injected through injection transformers. The switching pattern is generated by comparing both these signals.

The switching pattern generation and the output voltage control is done by hysteresis band voltage. Bands are present above and under reference voltage. Switching does not occur when the output voltage V_0 is present between the upper and lower limit (upper limit – V_H and lower limit – V_L). When the difference between the inverter voltage and reference pass the upper limit, the voltage will decrease. Similarly, if the difference reaches the lower limit then the voltage increases, as shown in Figure 2. The hysteresis band is the difference between V_H and V_L, i.e. $HB = V_H - V_L$.

The figure below shows the principle of hysteresis voltage control.



(a) (b)

Fig. 2. Principle of hysteresis controller (a); switching signals (b)

The voltage controllers are designed to operate independently. They are responsible for generating switching signals. The switching logic for a phase P is formulated as:

If $V_P < (V_{P_{\text{ref}}} - HB)$ Then the upper switch is OFF and the lower switch is ON.

If $V_P > (V_{P_{\text{ref}}} - HB)$ Then the lower switch is OFF and the upper switch is ON.

The main advantage of the hysteresis controller is its fast-transient response, low cost and ease of implementation. It has some limitations like generation of sub-harmonic components. At a lower modulation index switching frequency increases, as a result of which a signal leaves the hysteresis band each time the zero vector is turned on, variation of switching frequency.

In order to overcome the drawbacks of the hysteresis controller, the proportional plus resonance (PR) controller has been developed [32], which has the characteristics of a double integrator, has infinite gain at a certain frequency (resonance frequency), and has no attenuation outside this frequency. These characteristics make the PR controller very suitable in compensating for the harmonics in a very selective way. This also maintains a constant and balanced load voltage in the case of system disturbances, which should be the main objective of any control scheme.

4.2. PR controller

The PR controller has become one of the most popular controllers in comparison with the PI controller, due to its better performance [33]. Due to its capability to gain high fundamental frequency, it is capable to reject low-order harmonics. It also helps in mitigating grid harmonics (Fig. 3).

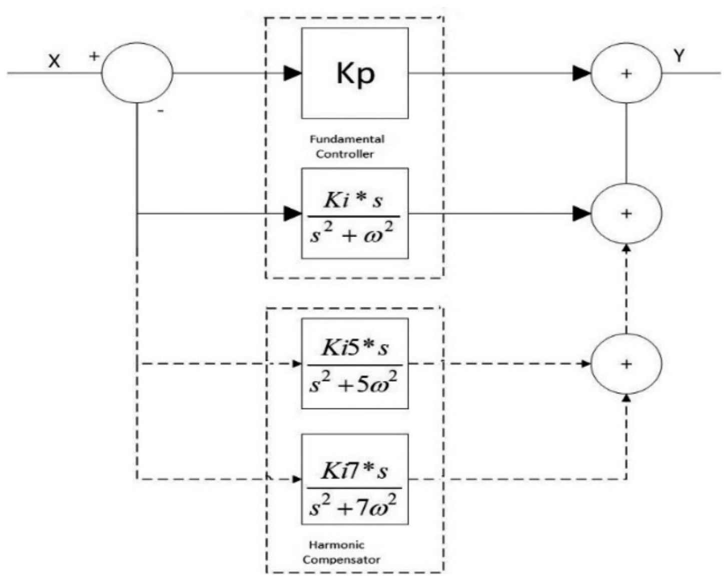


Fig. 3. PR controller and harmonic compensator structure

The ideal transfer function of the PR controller is given by:

$$G_p(s) = K_p + K_i \left(\frac{1}{s + j\omega} + \frac{1}{s - j\omega} \right), \tag{16}$$

$$G_p(s) = K_p + \frac{2K_i s}{s^2 + \omega_0^2} = \frac{2K_i s + K_p \left(s^2 + \omega^2\right)}{s^2 + \omega^2}. \tag{17}$$

Equation (17) is the ideal PR controller due to stability problems that occur due to infinite gain. The bandwidth of the PR controller is dependent on K_p [34].

The non-ideal PR controller is made by introducing damping to avoid these problems as shown below.

The non-ideal PR controller [35] is defined as:

$$G_p(s) = K_p + K_i \frac{2\omega s}{s^2 + 2\omega s + \omega_0^2}, \tag{18}$$

where K_p represents the proportional gain, which defines the system dynamics; a bandwidth, phase and gain margins, and in an equivalent DC system it can be tuned [36]. K_i is the integral gain. ω is the bandwidth around the AC frequency, ω_0 [37].

The gain of the PR controller is now finite with Equation (18) but provides a very small steady-state error [38]. Due to their finite precision the controller is more easily realizable in digital systems.

A major advantage of the PR controller is that at the fundamental frequency, similar to its resonating and controlling signal, other resonating and other blocks can be added in parallel with the fundamental block.

$$G_{p,h}(s) = \sum_{h=3,5,7\ldots} \frac{2K_{i,h}s}{s^2 + (h.\omega)^2}. \tag{19}$$

This means that specific harmonic components will be regulated, and the overall number of the controllers required will be reduced. When there are stability issues and the inverter currents start resonating, the PR control is added by tuning to its resonant frequency.

In order to eliminate the steady-state error, the PR controller introduces infinite gain at a selected resonant frequency. One of the main advantages of this controller is that, in controlling the AC signals, it eliminates the need for coordinate system transformation. This makes the PR controller suitable for power quality applications with high performance.

5. Results

Figure 4 is our basic line diagram. It shows a two-transmission line system, which is combined by the IPFC. V_s1 and V_s2 are the sending end voltages of 33 kV, and by using transformers T1 and T2, respectively, for both the lines, the voltage is stepped down to 11 kV. These lines are connected to high rating load on the receiving end. The IPFC is the back-to-back connection of VSC1 and VSC2 that are connected to transmission lines through injection transformers. R_1, R_2, X_{L1}, X_{L2}, L_1 and L_2 are the line resistance and reactance.

VSC1 and VSC2 are the voltage source converters. They help in the interconnection of two networks. The interconnection of two or more networks is done by the back-to-back connection of DC transmission links. The real power transferred is relatively independent of generated reactive power on the AC side by the voltage source converter. Because of this each bus is capable of controlling its own AC voltage.

To test the efficiency of the IPFC with the proposed control techniques, two case studies are considered. They are:

1. Transmission lines with and without the IPFC, when the system load is normal.
2. Transmission lines with and without the IPFC, when the system load is suddenly increased.

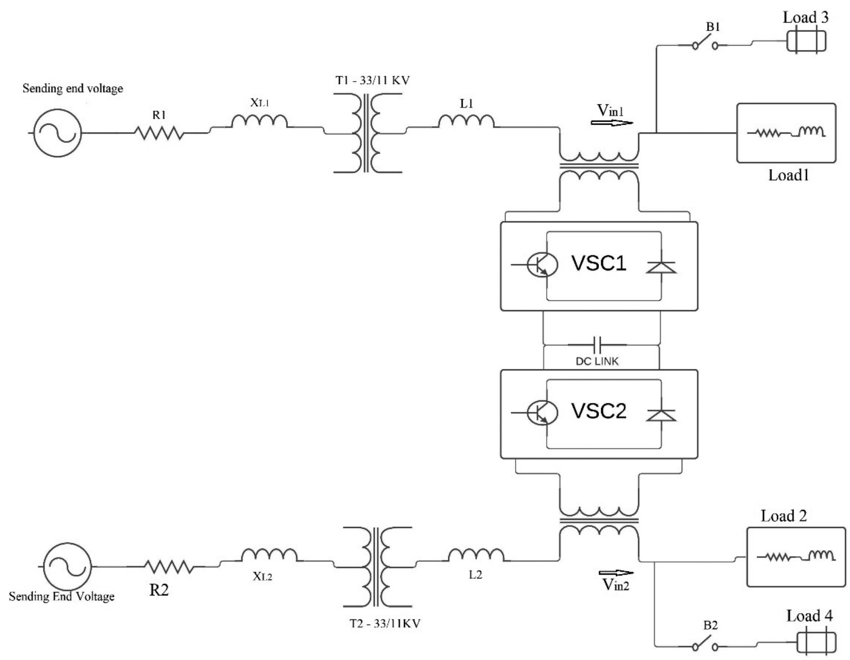


Fig. 4. Basic line diagram of IPFC

For the case studies a test system is implemented with the IPFC by using hysteresis and PR control algorithms. Pulses are generated to a cascaded 5-level inverter. The comparative analysis is made between the hysteresis controller and PR controller in the IPFC with a five-level cascaded inverter.

When the system load is high and when the IPFC is not present in the system, we can see a huge drop, output voltage dropped to 6 kV from the source or transmission voltage as shown in the below figure. Transmission line 2 also has the same voltage. This will show its impact on the source. So, in order to eliminate this and to balance the voltage FACTS devices are used (Fig. 5).

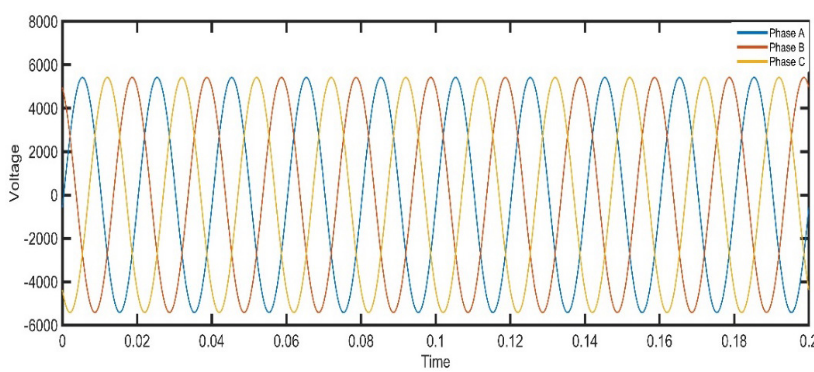


Fig. 5. When IPFC is not connected, voltage at the end of transmission line 1

When the system load is increased suddenly at some point then we can see a drop in voltage initially and when the system load is suddenly increased at 0.1 seconds the voltage drastically decreases and there are heavy harmonics seen in the system, which can be seen from Figure 6.

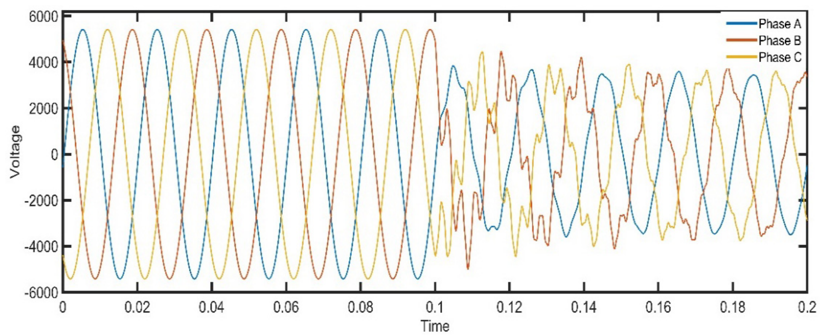


Fig. 6. Voltage at the end of transmission line 1, when the load is increased suddenly at 0.1 seconds in the absence of IPFC

Similarly, to the above case, when the load is suddenly increased at 0.1 seconds and now the system is connected with the IPFC, the system will be able to control the load voltage in the presence of the IPFC. Here the IPFC is designed with the hysteresis controller. The IPFC makes the system attain 11 kV voltage even though the load is suddenly increased at 0.1 seconds, but there are slight harmonics present in the system when the load is suddenly increased, which is seen in Figure 7. Transmission line 2 also has the similar output.

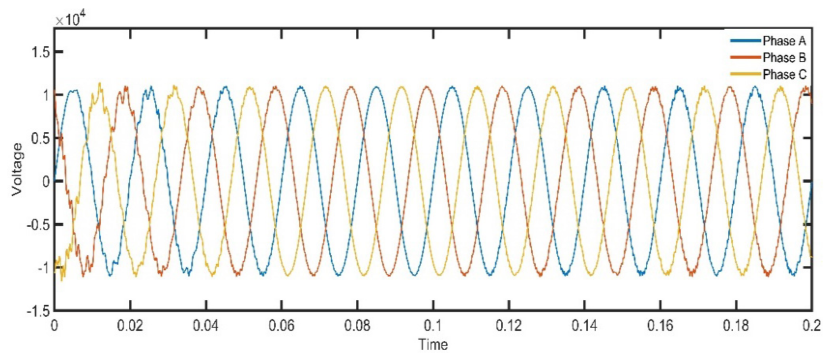


Fig. 7. Voltage of line 1 when the load is increased suddenly at 0.1 seconds in the presence of IPFC-hysteresis

When the load is suddenly increased in the presence of the IPFC with the proportional resonant (PR) controller, we can see that the output voltage is very smooth with very few disturbances (Fig. 8).

Figure 9 shows the RMS voltage of the transmission line in the presence of the hysteresis controller during heavy load on the system. With the hysteresis controller the RMS value is little fluctuating, while with the PR controller the RMS value is almost constant, as shown in Figure 10.

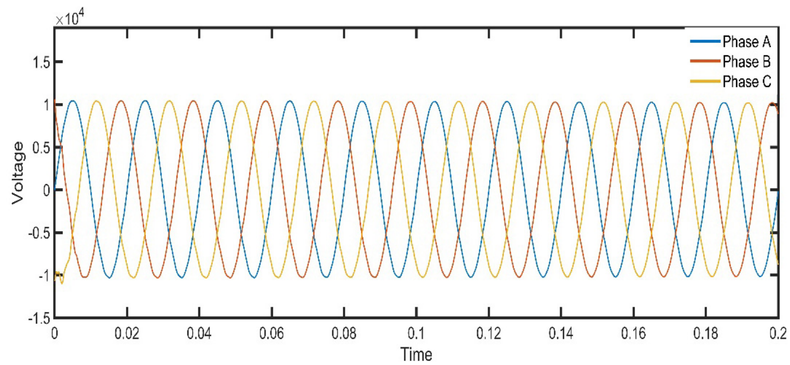


Fig. 8. Voltage of line 1, when the load is increased suddenly at 0.1 seconds in the presence of IPFC-PR

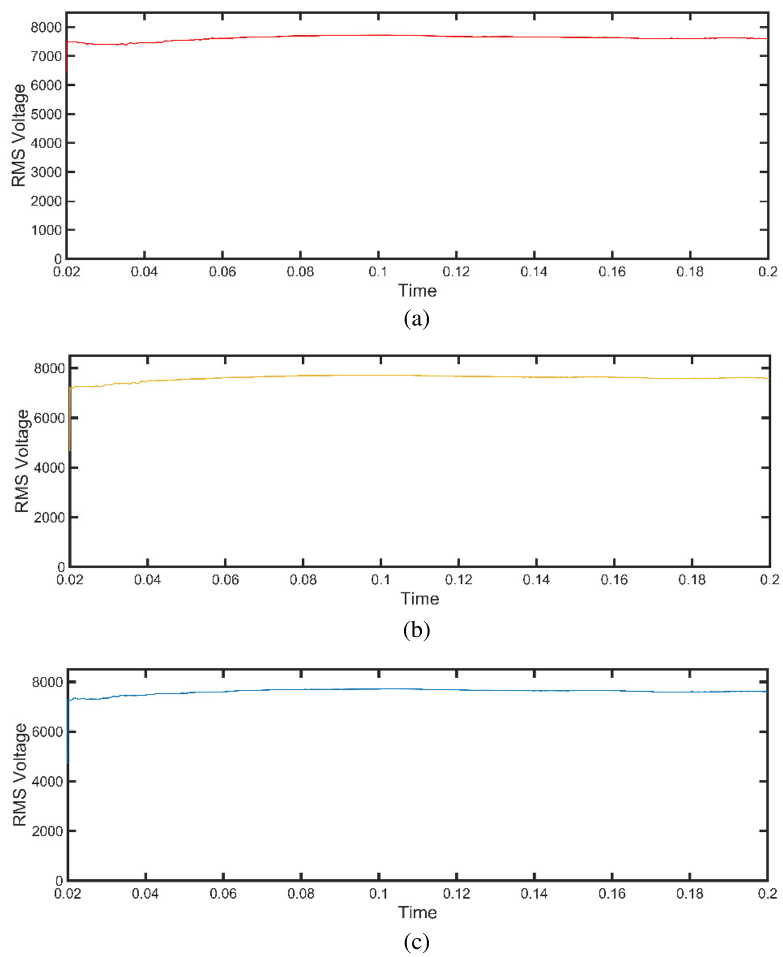


Fig. 9. RMS voltage in the presence of IPFC, when the load is increased suddenly at 0.1 seconds; (a), (b) and (c) with IPFC-hysteresis for R, Y, B phases, respectively

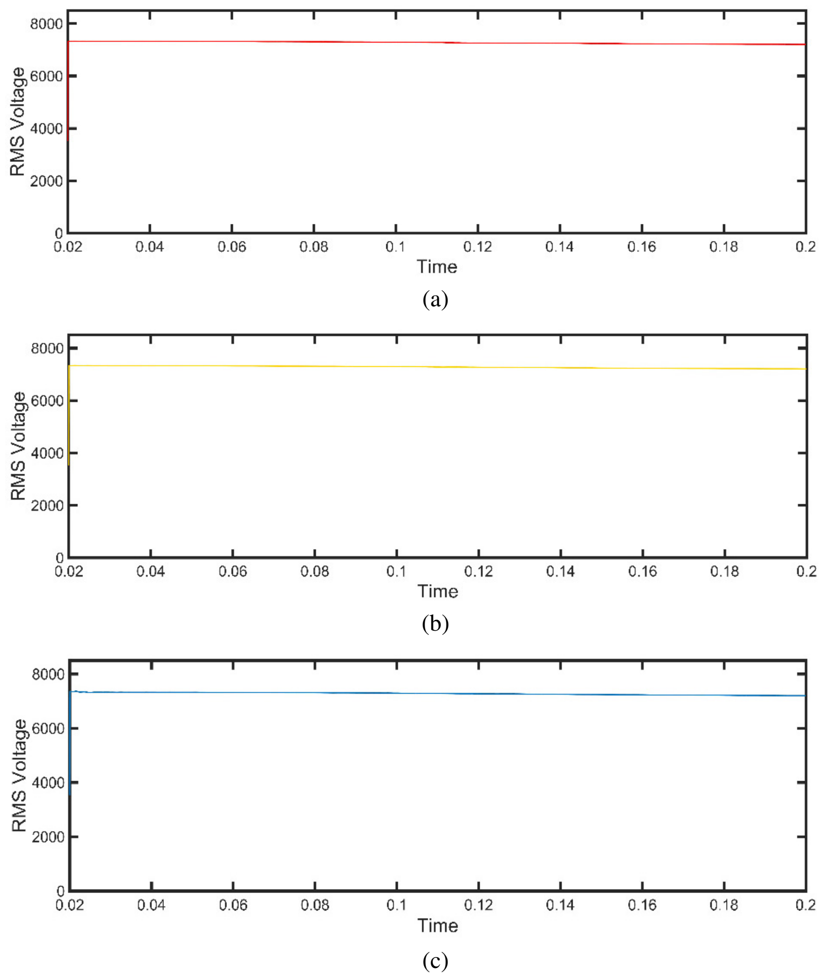


Fig. 10. RMS voltage in the presence of IPFC, when the load is increased suddenly at 0.1 seconds; (a), (b) and (c) with IPFC-PR for R, Y, B phases, respectively

From the below Figure 11, we can see that the overall output voltage total harmonic distortion (THD) is 1.75% in the presence of the IPFC with the PR controller, which is very little in comparison to the hysteresis controller, as shown in Figure 12.

Total harmonic distortion is the amount of distortions in voltage or current caused in a signal due to harmonics. In power systems THD is one of the key aspects and it should be as low as possible, usually it is expressed in percentage [39,40]. In power systems low harmonic distortions means less heating and low peak currents, which implies a good system.

The IPFC is tested with various control techniques and other FACTS devices [41]. The following table shows the THD of the IPFC during normal load and sudden increase in load with hysteresis and proportional resonant controllers. When the IPFC is tested with both the

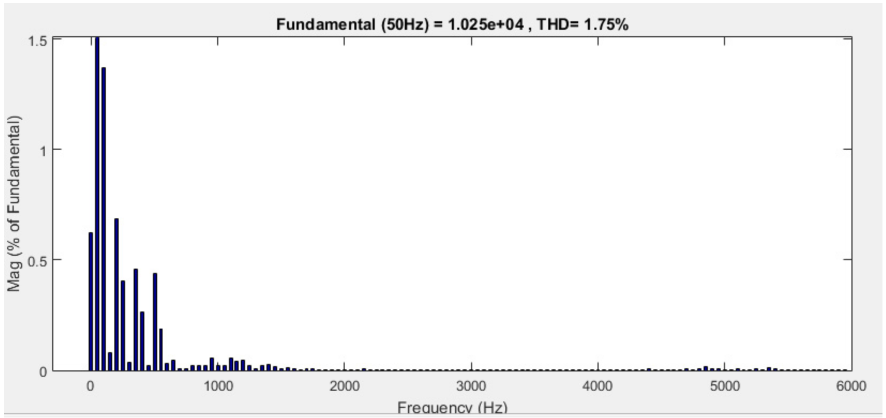


Fig. 11. THD of the system with IPFC-PR

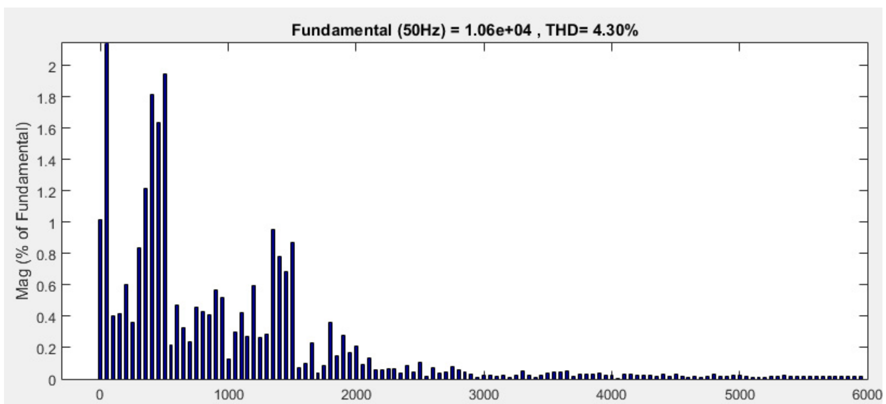


Fig. 12. THD of the system with IPFC-Hysteresis

hysteresis voltage controller and the proportional resonant controller, it is found that harmonics during normal load on the IPFC with the hysteresis controller is huge in comparison with the proportional resonant controller. The below table describes the percentage of harmonics present in voltage during control of the IPFC with hysteresis and PR controllers.

Table 1. THD summary for IPFC-HYSTERESIS and IPFC-PR.

	During normal load (%)		**With sudden increase in load (%)**	
	V	**I**	**V**	**I**
Hysteresis controller	5.35	23	4.30	21.10
PR controller	1.67	9.13	1.75	9.11

6. Conclusions

The IPFC interline power flow controller plays a key role in compensating for power among the multiple lines it is connected to. The control part of the IPFC plays a key role in this process, which is implemented by using different control techniques/algorithms like SPWM, SVM, hysteresis, proportional resonant controllers and many more. Real-time implementation of the IPFC with various controllers is the next step of our research. Here, a comparative analysis is done with a cascaded 5-level IPFC with hysteresis and PR control algorithms. Flexible transfer of power is seen between the networks with the usage of a 5-level cascaded inverter. This study concluded that the IPFC-PR is more efficient then the IPFC-hysteresis with lower harmonic content and smooth output voltage. Hence the IPFC with the PR controller is preferable for voltage-related problems in transmission lines.

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