

EFFECT OF SOLID-STATE ON LOAD DISTRIBUTION TRANSFORMER TAP-CHANGER ON POWER QUALITY ENHANCEMENT

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Abstract Recently electronic tap-changer has received more attention due to its quick response, better performance and simpler maintenance compared to the mechanical tap-changer. This paper presents the capability of the distribution transformer equipped with an electronic tap-changer for improving power quality. At this end, the analytical computation for determining the compensating limit of electronic tap-changer is given and then this system is simulated in order to show its capabilities for power quality enhancement. Meanwhile, the impact of the electronic tap-changer in power quality parameter improvement is compared with that of other custom power tools.

Key Words Index Terms- Power Quality, Electronic Tap-Changer, Distribution Transformer, Custom Power Tools

چکیده اخیراً "تپ چنجر الکترونیکی به دلیل پاسخ سریع، عملکرد بهتر و نگهداری ساده تر در مقایسه با تپ چنجر مکانیکی مورد توجه بیشتری قرار گرفته است. این مقاله قابلیت ترانسفورماتور توزیع مجهز به یک تپ چنجر الکترونیکی را در بهبود کیفیت توان ارائه می دهد. بدین منظور، محاسبه تحلیلی برای تعیین حد جبران سازی تپ چنجر الکترونیکی داده شده و سپس این سیستم شبیه سازی شده تا قابلیت های آنرا در بهبود کیفیت توان نشان دهد. در ضمن، تاثیر تپ چنجر الکترونیکی بر بهبود پارامتر کیفیت توان با سایر ابزار مرسوم مورد مقایسه قرار گرفته است.

1. INTRODUCTION

Power quality of electrical energy is a measure of quality of service at the point of common coupling between an energy provider and an energy user [1]. Various factors cause system power quality to deteriorate including effects due to polluting loads such as electric motors, arc furnaces and power electronics equipment. In many alternating current (AC) distribution systems, based on the requirements of critical new loads such as computers, microprocessor automatic control systems, robots and adjustable speed drives, a better level of electricity service is demanded by users. Different power quality enhancement methods can be classified based on the level of application in the distribution system as shown in Figure 1 [2].

Improvement at level 1 means making non-critical the devices connected to the power system

against power quality problems. At this level the devices must be designed and built such that they can withstand the power quality problems encountered and at the same time have acceptable performance. Improvement at level 2 means protecting critical loads (such as control devices of a factory) by protection devices. Improvement at level 3 means application of a protection device for all loads. Improvements level 2 and 3 include Ferro resonant transformers, various UPS, etc.

Improvements at level 4 are the solutions at the power system side, not the user side. In this level, the problems of power quality are reduced using tools in distribution network. These tools are similar with FACTS tools from the power circuit structure point of view, and called Custom Power tools. Examples of such tools are: dynamic voltage restorer (DVR), distribution static compensator (DSTATCOM), active filter, solid state breaker (SSB), unified power quality controllers (UPQC)

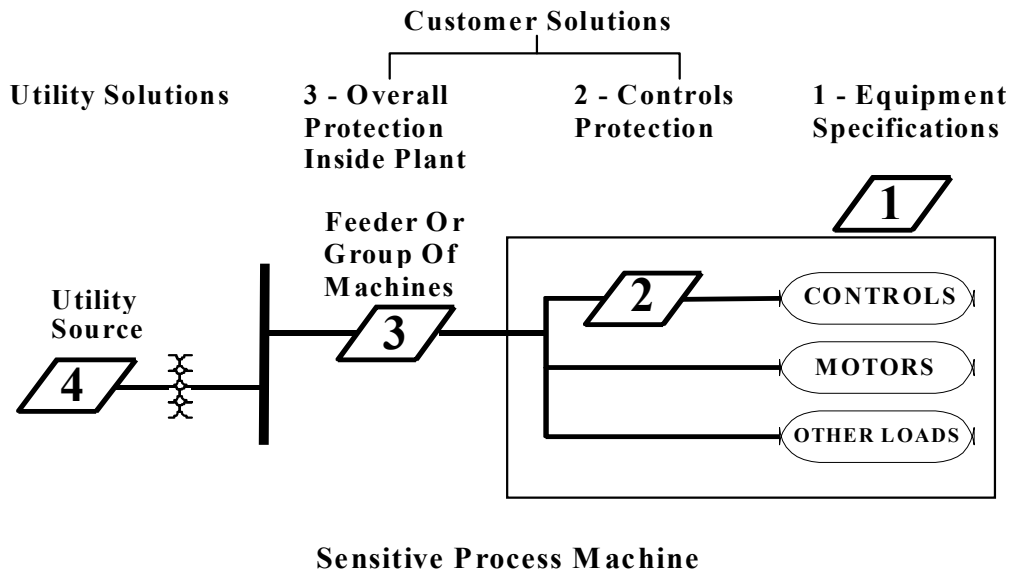


Figure 1. Different power quality methods based on the level of application in the distribution network.

and solid state transfer switches (SSTS) [3-8].

Many of power quality problems spring from the polluting loads (and not the deficiencies of the power system), thus, in addition to improvements in level 1 to 4, load restrictions are required in order to reduce power quality problems and prevent the destructive effects of the polluting loads. Levels 1 to 3 of the power quality improvement methods are applied on the user side, which can be very costly for the users. This may not be acceptable for users and they expect these problems to be solved on the power system side (level 4) if possible.

One of the devices that have been recently proposed as a custom power tool is the full electronic tap-changer [9-11]. This paper simulates this device and studies its capabilities for power quality improvement and makes comparisons with other custom power tools. To this end, parameters and terminologies of the power quality are reviewed in section II. The structure and principles of operation of three types of the important and new custom power tools, DVR, DSTATCOM and

UPQC are noted in section III, for comparison. In section IV, an electronic tap-changer is introduced and its capabilities are proposed and simulated. Finally, capabilities of the electronic tap-changers are compared with DVR and DSTATCOM in section V. Section VI concludes the paper.

2. POWER QUALITY PARAMETERS

Power quality parameters are used to describe a wide range of supply voltage waveform distortions. It is important to precisely classify the parameters relevant to power quality in order to recognize them, to find the generation origin and ultimately to obey cancellation techniques. Table 1 represents this classification according to IEEE STD 1159. In this table supply waveform distortions have been classified into seven overall parts. Transients are temporary phenomena, which are divided into impulse and oscillatory components. Short duration variations are normally

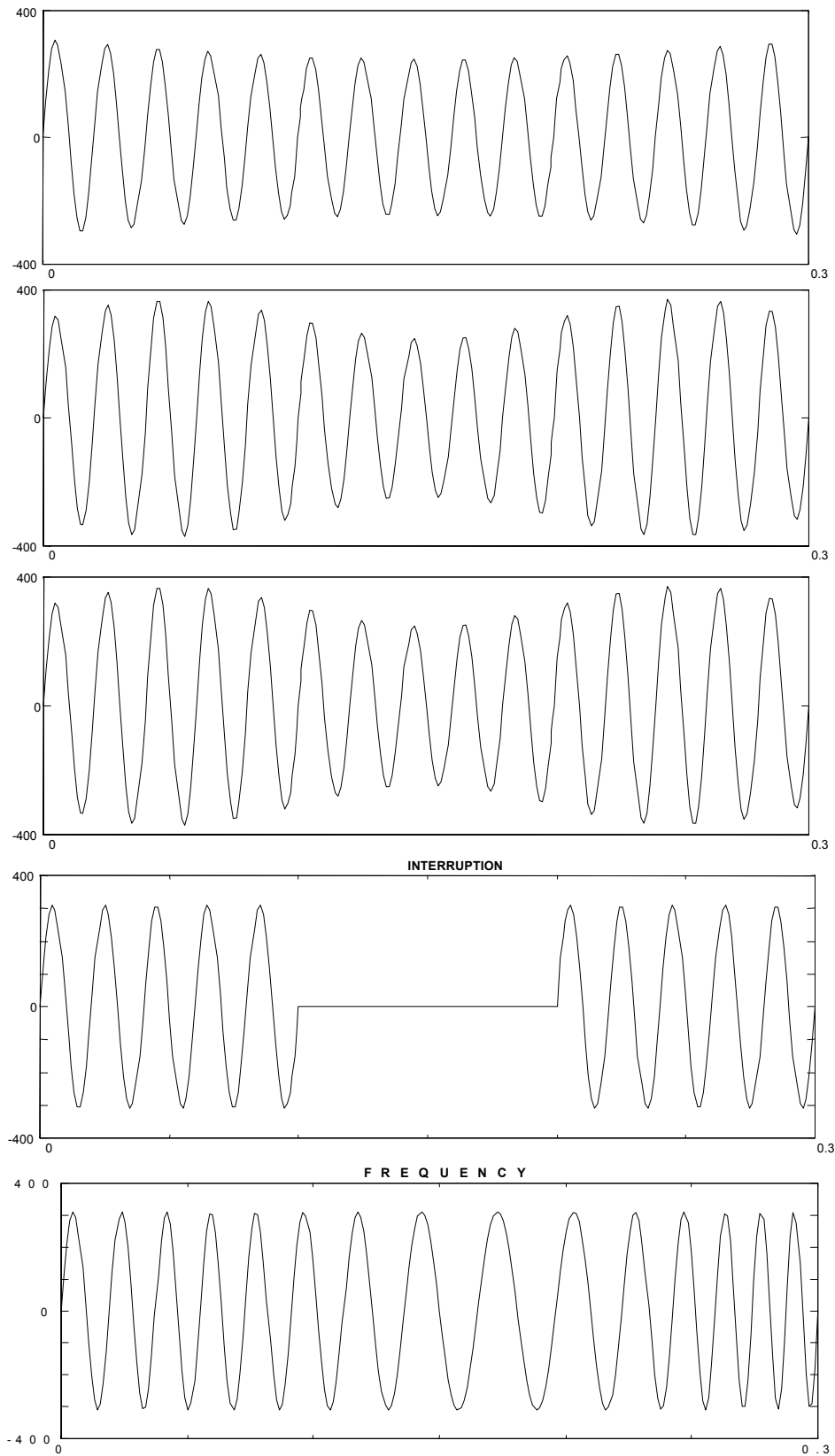


Figure 2. Different kinds of voltage waveform distortions.

TABLE 1. Classification of Power Quality Parameters.

Number	Category	Typical spectral content	Typical duration	Typical voltage magnitude
1.0	Transient			
1.1	Impulsive			
1.1.1	Nanosecond	5 ns rise	< 50ns	
1.1.2	Microsecond	1 μ s rise	50ns-1ms	
1.1.3	Millisecond	0.1ms rise	>1ms	
1.2	Oscillatory			
1.2.1	Low frequency	<5kHz	0.3-50ms	0-4 pu
1.2.2	Medium frequency	5-500 kHz	20 μ s	0-8pu
1.2.3	High frequency	0.5-5MHz	5 μ s	0-4 pu
2.0	Short duration variation			
2.1	Instantaneous			
2.1.1	Sag		0.5-30 cycles	0.1-0.9 pu
2.1.2	Swell		0.5-30 cycles	1.1-1.9 pu
2.2	Momentary			
2.2.1	Instantaneous		0.5 cycles-3s	<0.1 pu
2.2.2	Sag		30 cycles-3s	0.1-0.9 pu
2.2.3	Swell		30 cycles-3s	1.1-1.4 pu
2.3	Temporary			
2.3.1	Instantaneous		3 s-1 min	<0.1 pu
2.3.2	Sag		3 s-1 min	0.1-0.9 pu
2.3.3	Swell		3 s-1 min	1.1-1.2 pu
3.0	Long duration variation			
3.1	Interruption		>1 min	
3.2	Under voltages		>1 min	
3.3	Over voltages		>1 min	
4.0	Voltage imbalance		Steady state	
5.0	Waveform distortion			
5.1	DC offset		Steady state	
5.2	Harmonics		Steady state	
5.3	Inter harmonics		Steady state	
5.4	Notching		Steady state	
5.5	Noise		Steady state	
6.0	Voltage fluctuation			
7.0	Power frequency variation			

caused by faults and are classified into immediate, instantaneous and temporary cases. Long-term variations are the result of load changes and switching. The unbalanced loads cause three-phase unbalanced voltages. Waveform distortions can be caused by steady-state harmonics. When the load current varies flicker occurs. Such loads

lead to voltage amplitude fluctuations. Power system frequency depends directly on the generator rotating speed which itself relates to the generator load. Frequency will vary over the period of the load change. Figure 2 presents some of the above-mentioned voltage waveform distortions.

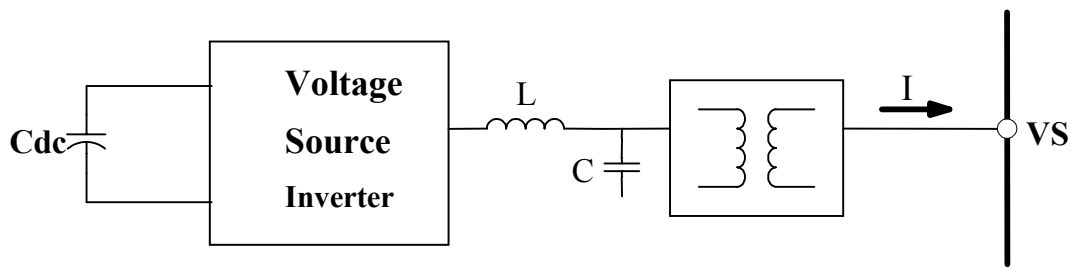


Figure 3. Basic structure of a DSTATCOM.

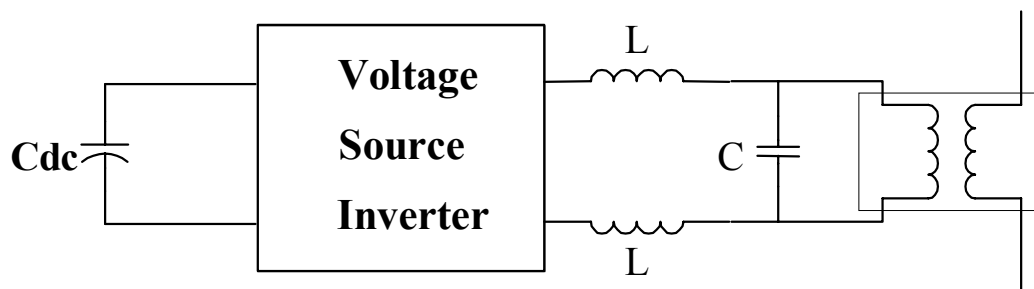


Figure 4. Basic structure of DVR.

3. CUSTOM POWER TOOLS

Power electronic devices for protecting the users against power quality problems of distribution system are proposed as custom power tools. The most important of these devices are DVR, DSTATCOM and UPQC. Voltage source inverter is a converter used in the all above-mentioned tools. In order to be able to compare these tools with electronic tap-changer, the above-mentioned tools are briefly described in the following section.

A: DSTATCOM:

Figure 3 presents the basic structure of a DSTATCOM which operates in parallel with the mains. This tool is adjustable as a current source, thus it is capable to compensate capacitive or inductive components.

B. DVR

Fig. 4 shows the basic structure of DVR that operates in series with the mains and injects a compensating voltage. Control system of DVR

compares the mains voltage with the reference voltage and then injects the required voltage. This tool is taken as an adjustable voltage source and it is capable to compensate the voltage.

C. UPQC

A UPQC set consists of DVR and a DSTATCOM. Figure 5 shows the basic structure of the tool. This tool is able to compensate in parallel (current compensating) and in series (voltage compensating), thus allowing improved flexibility.

It is noted that in each of the above-mentioned tools the energy of capacitor C_{dc} (VSI input) can be taken from the mains or an energy storage system (such as battery).

4. ELECTRONIC TAP-CHANGER

High voltage and high current power electronic switches have made it possible to design full-electronic tap-changers. In this type of tap-changer, there are no moveable mechanical parts and thus it

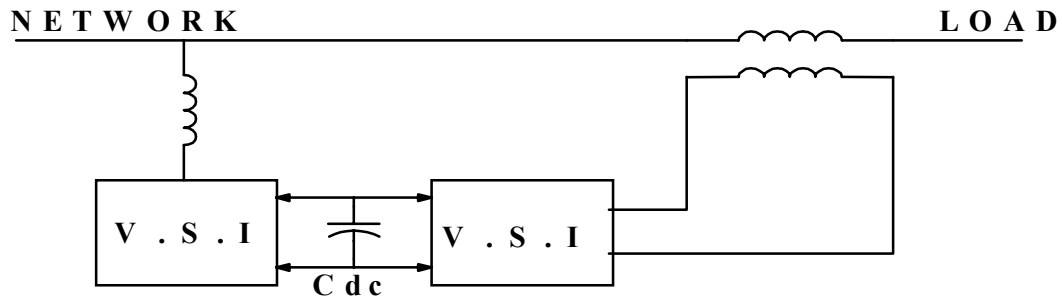


Figure 5. Basic structure of UPQC.

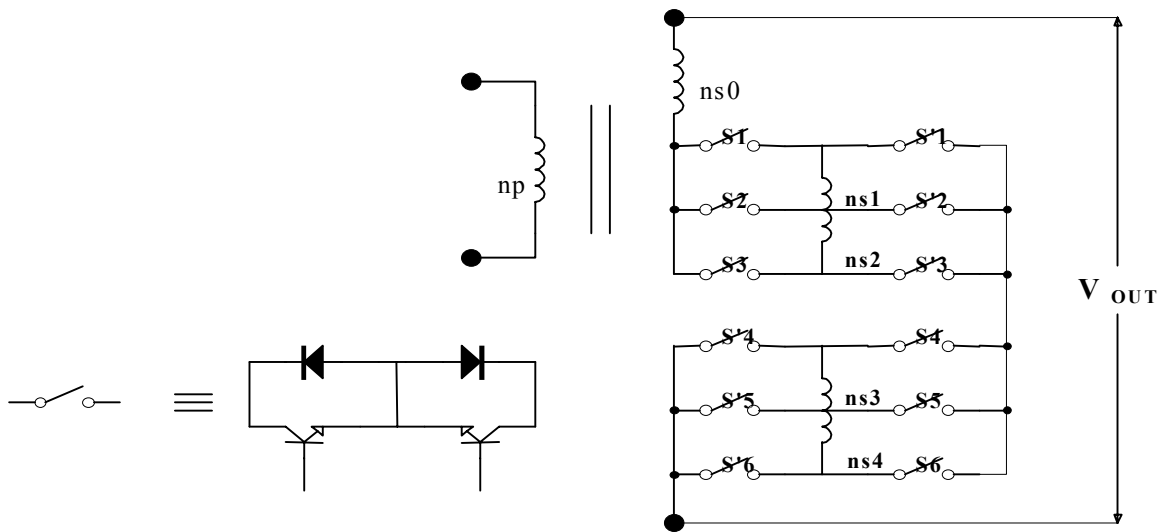


Figure 6. An optimal structure of electronic tap-changer.

is quicker, lighter and efficient, with low volume. Meanwhile, the maintenance cost of electronic tap-changers is very low compared to the conventional mechanical tap-changer. Taking into account the above-mentioned advantages many attempts have been made to offer practical designs [9-13], with high reliability, low cost, with protection against short circuits and over voltages. The application of this device on the distribution transformers is proposed as one of the custom power tools [9-11]. In this section, this device is simulated and its capabilities are studied in power quality improvement. Figure 6 shows an optimal structure of an electronic tap-changer which is simulated in

this paper.

The system is simulated by power system blocks set of Simulink software. The simulation model has been presented in Figure 7. Since there is a transformer with maximum of two secondary windings in Simulink, the transformer with several secondaries shown in Figure 6, three transformers have been used where their primaries are in parallel. In order to connect the transformer terminals to each other, multi-output and multi-input bus bar blocks have been employed. The semiconductor switches have been also modeled by an ideal switch block. Since the overall performance of an electronic tap-changer is

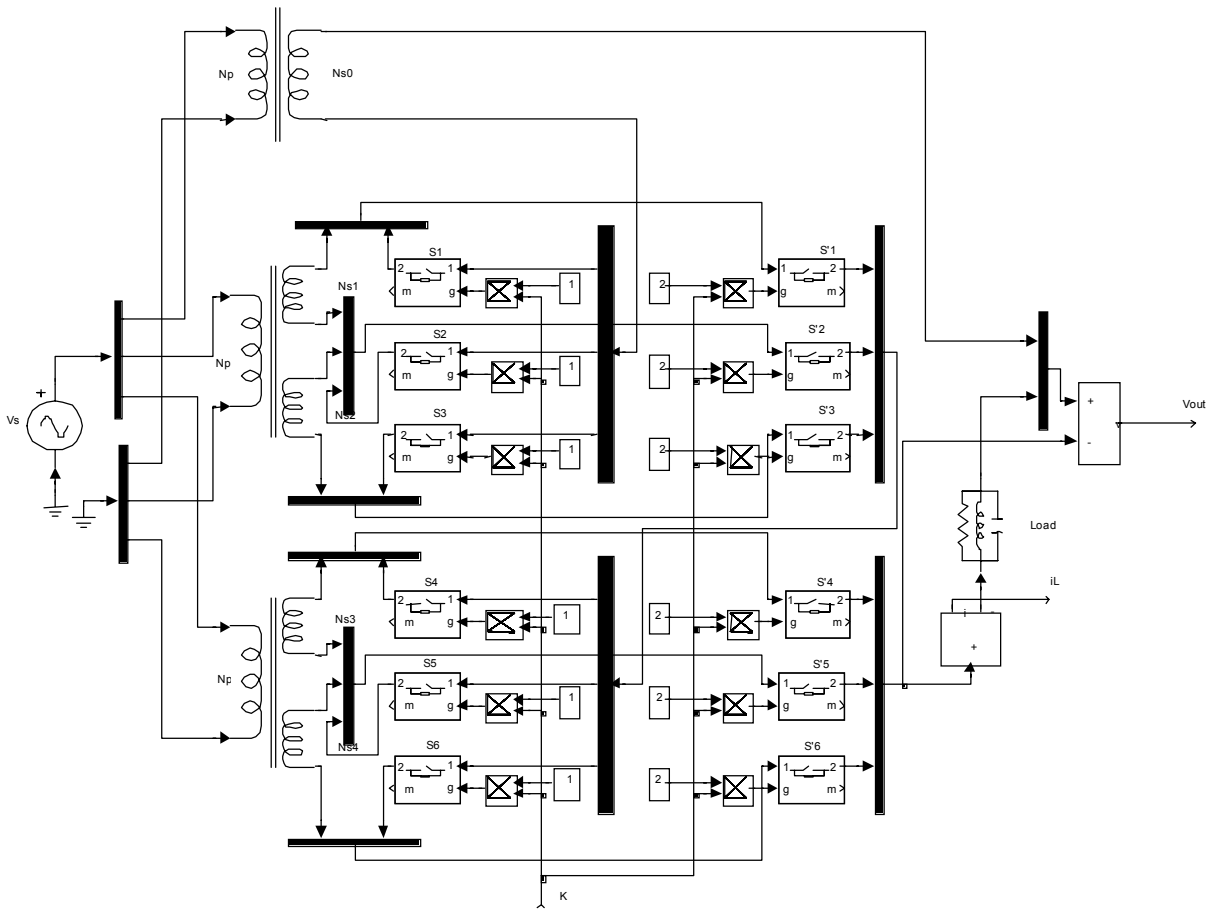


Figure 7. Simulation model of tap-changer of Figure 6 using Simulink power system blocks.

considered, this assumption will not cause restrictions in the results obtained. Forty-nine different positions for V_{out} are obtained based on the states of twelve switches: $S_1, S'_1, S_2, S'_2, \dots, S_6, S'_6$. Table 2 shows these 49 positions for the output voltage of transformer, having the following turns ratio with $V_p=220$ V.

$$\begin{aligned} n_{s0}/n_p=210/220, \quad n_{s1}/n_p=2/220 \quad n_{s2}/n_p=4/220, \\ n_{s3}/n_p=14/220, \quad n_{s4}/n_p=28/220 \end{aligned} \quad (1)$$

In model of Figure 7, command K is equivalent with the row number in Table 2. The data in Table 2 has been given by a look-up-table when K refers to the row number; the states of the proposed switches are created. The contents of Table 2 are

entered to six two-row look-up-tables (the reason is the limitation of look-up-tables in Simulink software). Information due to each pair of switches S_i and S'_i are summarized in a look-up-table. A linear RLC circuit has been used as a load. Varying the components of RLC circuit can change peak load current and also power factor.

In fact, Figure 7 can fully model the power part of the electronic tap-changer. V_{out} and I_L (load current) signals return to the control circuit as feedback, and output of the control circuit determines command K (state of twelve-switches). The control circuit operates as such that V_{out} remains constant against input voltage and load current variations. In order to minimize the losses and the switching stresses, the states of the switches are allowed to vary only when it crosses

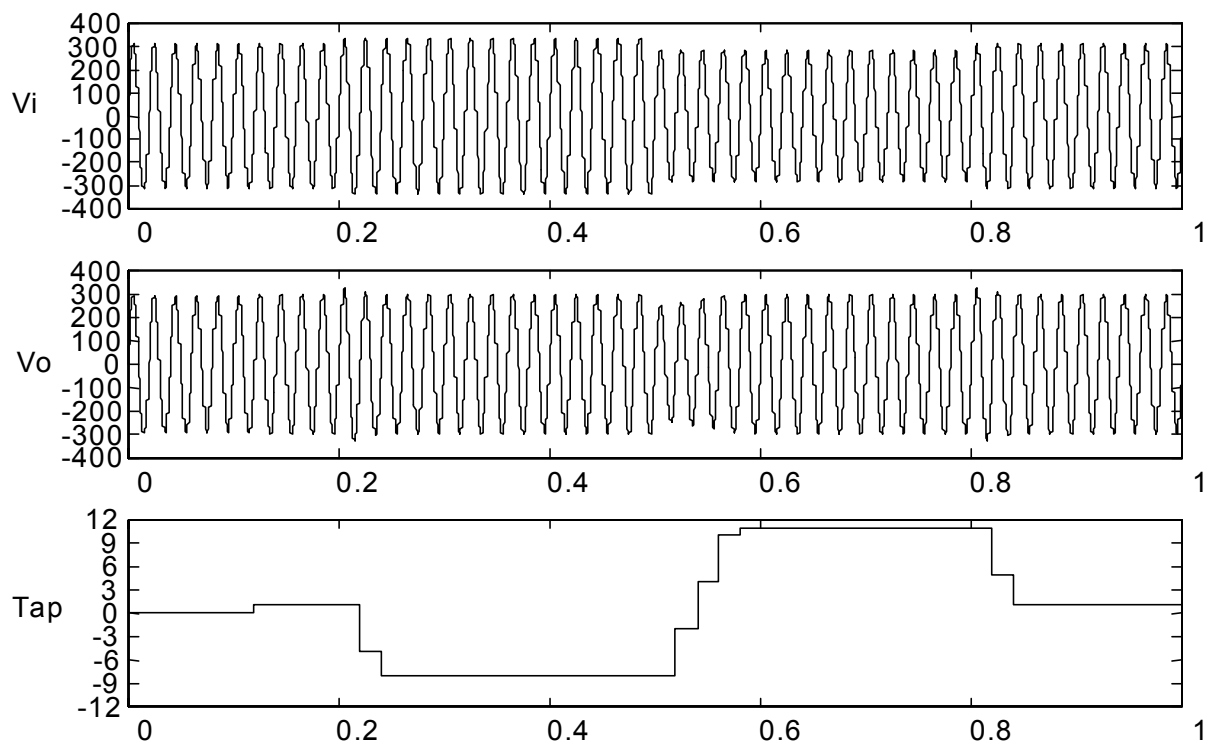


Figure 8. Simulation results for variations of input voltage.

the zero. Thus, the command to vary K is issued when I_L crosses zero. Therefore, there are two possibilities of varying the switch state in every cycle. Here one of advantages of the electronic tap-changer is clear. In a mechanical tap-changer, one state of the switch takes several seconds, while in an electronic tap-changer such action is possible in every half-cycle. Meanwhile, it is noted that changing the position of the mechanical tap-changer come along with losses and stress while changing of electronic tap-changer occurs at zero current (ZCS) in which the losses and stress are minimal. On the other hand, in mechanical tap-changer, switch states are changed step by step while it is possible to jump from $K=1$ to $K=49$ in every half-cycle in an electronic tap-changer which speeds up the control rapidly. The advantage of the solid-state tap-changer jump can be considered as an inherent feature of this tap-changer. However, practical realization of this advantage and its application requires necessary considerations related to the control and power system. Rapid rise

of voltage causes a large capacitive current and this may damage the tap-changer or generate a notch in the network, but the level of this current is determined based on the capacitance of the load system. It is noted that simulation for six steps in the tap-changer is due to the control system used and not limitation of the tap-changer.

In order to remove the high capacitive currents in step changes with large jumping it is possible to employ ZVC, but decision on the ZVC or ZCS depends on the nature of the load. Certainly if the load is largely capacitive, the ZVS may lead to lower losses, otherwise, ZCS is preferred due to its lower losses.

Figure 8 exhibits the simulation results for variations of input voltage from $220 V_{rms}$ to $240 V_{rms}$ and then $200 V_{rms}$ and finally returning to $220 V_{rms}$ at $t=0.2s$, $t=0.5s$ and $t=0.8s$. In this simulation the control system does not allow more than six units change in each change of K . It is observed that the output voltage is quickly regulated. Figure 9 presents the simulation results for the following

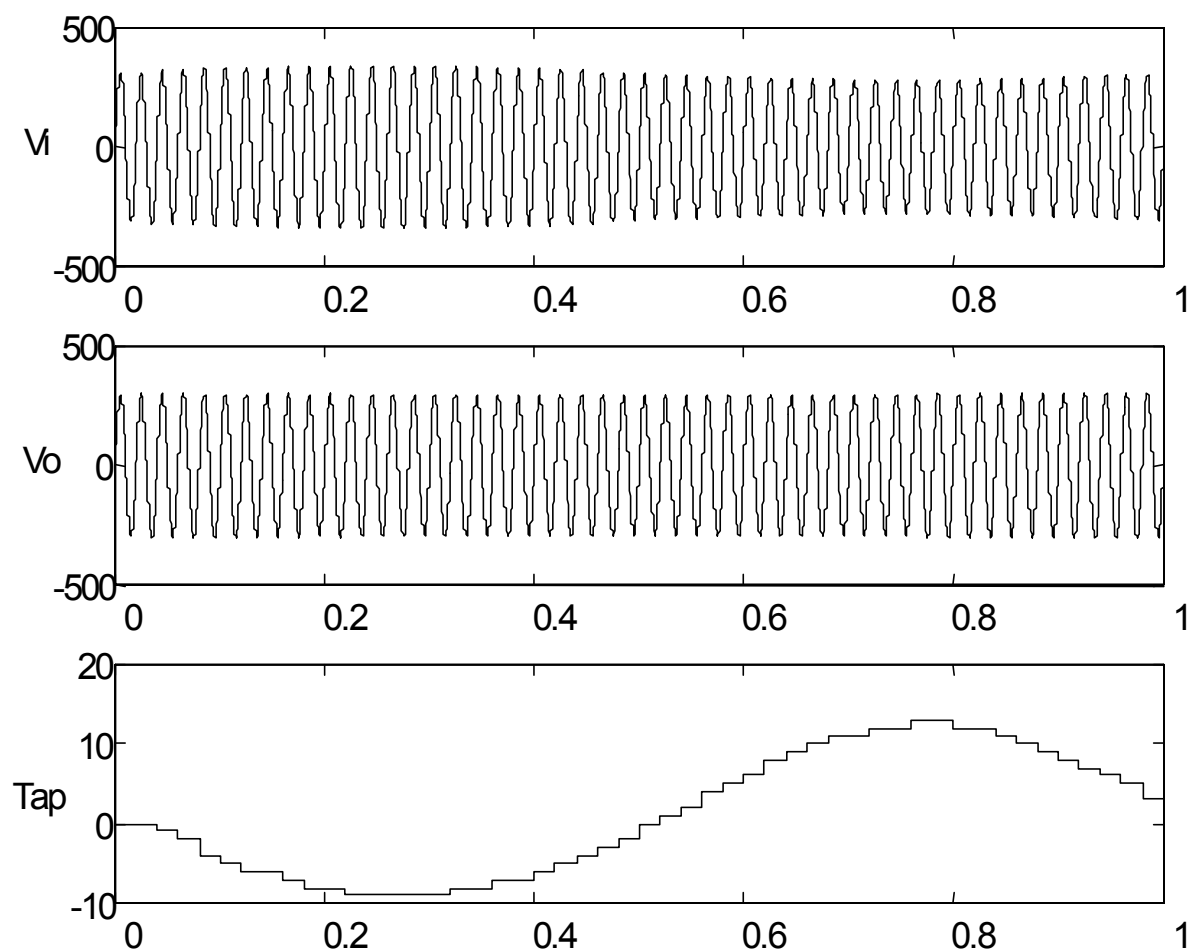


Figure 9. Simulation results for variations of sinusoidal input voltage.

input voltage waveform:

$$V_i = \frac{220}{\sqrt{2}} \sin 100\pi t (1 + 0.1 \sin 2\pi t) \quad (1)$$

As seen the envelop of the output voltage is not varied sinusoidally.

So far, the possibility of application of a high frequency modulation technique in switching of solid-state switches has not been discussed. This feature is realized considering the controllability and quick operation of the solid-state switches. In

fact, in the above-mentioned technique, similar to the mechanical tap-changer, switching is carried out only during the tap-changing period and in the remaining time the states of switches are fixed.

The major advantage of this technique is lower switching losses, non-existing troublesome switching harmonics in the steady state. Although high frequency harmonics are produced (which must be eliminated by a proper filter) and larger switching losses exist (which must be minimized by soft-switching techniques) in the high frequency modulation technique, the output voltage will be continuously controlled and the output voltage waveform will be instantaneously modified.

TABLE. 2. Different Values of Output Voltages Versus Twelve Switch Positions of Electronics Tap-Changer.

No.	States of switches												$V_{no} - V_{out}$ (V)
	S ₁	Ś ₁	S ₂	Ś ₂	S ₃	Ś ₃	S ₄	Ś ₄	S ₅	Ś ₅	S ₆	Ś ₆	
1	0	1	0	0	1	0	0	1	0	0	1	0	- 48
2	0	0	0	1	1	0	0	1	0	0	1	0	- 46
3	0	1	1	0	0	0	0	1	0	0	1	0	- 44
4	1	1	0	0	0	0	0	1	0	0	1	0	- 42
5	1	0	0	1	0	0	0	1	0	0	1	0	- 40
6	0	0	1	0	0	1	0	1	0	0	1	0	- 38
7	1	0	0	0	0	1	0	1	0	0	1	0	- 36
8	0	1	0	0	1	0	0	0	0	1	1	0	- 34
9	0	0	0	1	1	0	0	0	0	1	1	0	- 32
10	0	1	1	0	0	0	0	0	0	1	1	0	- 30
11	1	1	0	0	0	0	0	0	0	1	1	0	- 28
12	1	0	0	1	0	0	0	0	0	1	1	0	- 26
13	0	0	1	0	0	1	0	0	0	1	1	0	- 24
14	1	0	0	0	0	1	0	0	0	1	1	0	- 22
15	0	1	0	0	1	0	0	1	1	0	0	0	- 20
16	0	0	0	1	1	0	0	1	1	0	0	0	- 18
17	0	1	1	0	0	0	0	1	1	0	0	0	- 16
18	1	1	0	0	0	0	0	1	1	0	0	0	- 14
19	1	0	0	1	0	0	0	1	1	0	0	0	- 12
20	0	0	1	0	0	1	0	1	1	0	0	0	- 10
21	1	0	0	0	0	1	0	1	1	0	0	0	- 8
22	0	1	0	0	1	0	1	1	0	0	0	0	- 6
23	0	0	0	1	1	0	1	1	0	0	0	0	- 4
24	0	1	1	0	0	0	1	1	0	0	0	0	- 2
25	1	1	0	0	0	0	1	1	0	0	0	0	0
26	1	0	0	1	0	0	1	1	0	0	0	0	2
27	0	0	1	0	0	1	1	1	0	0	0	0	4
28	1	0	0	0	0	1	1	1	0	0	0	0	6
29	0	1	0	0	1	0	1	0	0	1	0	0	8
30	0	0	0	1	1	0	1	0	0	1	0	0	10
31	0	1	1	0	0	0	1	0	0	1	0	0	12
32	1	1	0	0	0	0	1	0	0	1	0	0	14
33	1	0	0	1	0	0	1	0	0	1	0	0	16
34	0	0	1	0	0	1	1	0	0	1	0	0	18
35	1	0	0	0	0	1	1	0	0	1	0	0	20
36	0	1	0	0	1	0	0	0	1	0	0	1	22
37	0	0	0	1	1	0	0	0	1	0	0	1	24
38	0	1	1	0	0	0	0	0	1	0	0	1	26
39	1	1	0	0	0	0	0	0	1	0	0	1	28
40	1	0	0	1	0	0	0	0	1	0	0	1	30
41	0	0	1	0	0	1	0	0	1	0	0	1	32
42	1	0	0	0	0	1	0	0	1	0	0	1	34
43	0	1	0	0	1	0	1	0	0	0	0	1	36
44	0	0	0	1	1	0	1	0	0	0	0	1	38

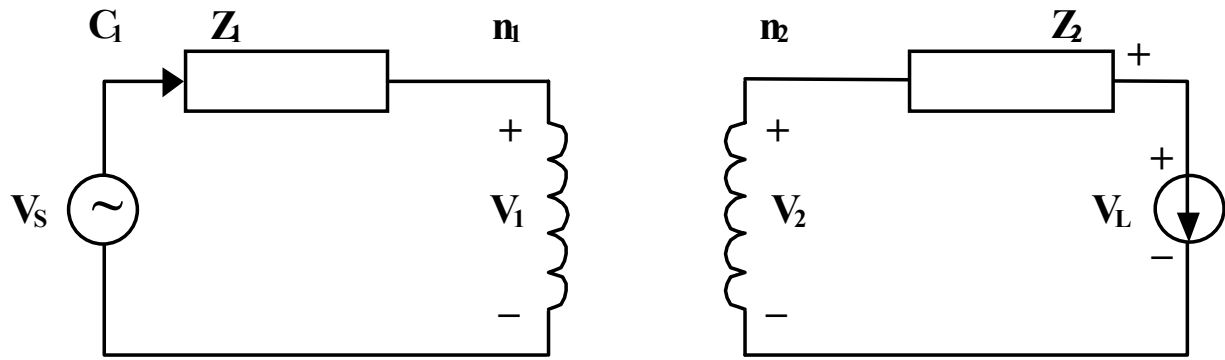


Figure 10. A model for calculation of compensating range of tap-changer.

It is concluded that if a high frequency modulation is used in an electronic tap-changer, this system can better perform its duties as tap-changer (high speed and possibility of quick jumps) and possibility of controlling the output voltage instantly. Present work and simulations emphasize of the solid-state tap-changer in which there are possibility of tap-changing only when cross the zero (every 10 ms). Possibility of using high frequency modulation in the solid-state tap-changer has been discussed in Reference 9.

It must now be determined that how much voltage drop may be compensated by a tap-changer. Consider Figure 10, where small letters denote time-dependent parameters and capital letters show the phasors. In this model, the phase difference between i_L and v_L is θ_L . Thus, the following equation is obtained for V_L :

$$V_L = XV_s - X^2 Z_1 I_L - Z_2 I_L \quad (2)$$

where $X=n_2/n_1$. If load impedance is Z_L , (2) will be as follows:

$$V_L = \frac{XV_s}{1 + X^2 \frac{Z_1}{Z_L} + \frac{Z_2}{Z_L}} \quad (3)$$

The aim is by varying i_L and v_s , the amplitude of v_L remains constant. If this constant value is

denoted by V_c then:

$$\left(\frac{|V_s|}{|V_c|}\right)^2 = \left[\frac{1}{X} + \frac{|Z_2|}{X|Z_L|} \cos(\theta_2 - \theta_L) + \frac{X|Z_1|}{|Z_L|} \cos(\theta_1 - \theta_L)\right]^2 + \left[\frac{X|Z_1|}{|Z_L|} \sin(\theta_1 - \theta_L) + \frac{|Z_2|}{X|Z_L|} \sin(\theta_2 - \theta_L)\right]^2 \quad (4)$$

It is seen that the adjustable range of X for making V_L equal to V_c depends on V_c , $|V_s|$, Z_1 , Z_2 , Z_L , θ_1 , θ_2 and θ_L . X are obtained by solving the 4th order equation (4). If all impedance in Figure 10 are taken to be resistive, i.e. $\theta_1=\theta_2=\theta_L=0$, (4) will be simplified as:

$$X^2 \frac{Z_1}{Z_L} + \frac{Z_2}{Z_L} - X \frac{V_s}{V_c} + 1 = 0 \quad (5)$$

There is solution for X of (5) if the roots are real and positive. It can be shown that (6) is the necessary and sufficient condition for positive and real solution for (5).

$$\left(\frac{|V_s|}{|V_c|}\right)^2 \geq 4\left(1 + \frac{Z_2}{Z_L}\right) \frac{Z_1}{Z_L} \quad (6)$$

Assuming $Z_1 Z_2 \leq Z_L^2$, Equation 6 will be simplified

TABLE 3. Comparison of Capabilities of Electronic Tap-Changer With Dstatcom For Eliminating The Power Quality.

No.	Category	Electronics Tap-Ch. With Pwm	Electronics Tap-Ch.	DVR	Dstatcom
1.0	Transient				
1.1	Impulsive				
1.1.1	Nanosecond	No	No	No	No
1.1.2	Microsecond	No	No	No	No
1.1.3	Millisecond	Yes	No	Yes	Yes
1.2	Oscillatory				
1.2.1	Low frequency	Yes	No	Yes	Yes
1.2.2	Medium frequency	No	No	No	No
1.2.3	High frequency	No	No	No	No
2.0	Short duration variation				
2.1	Instantaneous				
2.1.1	Sag	Yes	Yes	Yes	No
2.1.2	Swell	Yes	Yes	Yes	No
2.2	Momentary				
2.2.1	Interruption	No	No	No	No
2.2.2	Sag	Yes	Yes	Yes	No
2.2.3	Swell	Yes	Yes	Yes	No
2.3	Temporary				
2.3.1	Interruption	No	No	No	No
2.3.2	Sag	Yes	Yes	Yes	No
2.3.3	Swell	Yes	Yes	Yes	No
3.0	Long duration variation				
3.1	Interruption	No	No	No	No
3.2	Under voltages	Yes	Yes	Yes	Yes
3.3	Over voltages	Yes	Yes	Yes	Yes
4.0	Voltage imbalance				
5.0	Waveform distortion				
5.1	DC offset	Yes	Yes	Yes	No
5.2	Harmonics	Yes	No	Yes	No
5.3	Interharmonics	Yes	No	Yes	No
5.4	Notching	Yes	No	Yes	No
5.5	Noise	No	No	No	No
6.0	Voltage fluctuation	Yes	Yes	Yes	Yes
7.0	Power frequency variation	No	No	No	No

as follows:

$$\left(\frac{|V_s|}{|V_c|}\right)^2 \geq 4 \frac{Z_1}{Z_L} \quad (7)$$

X is changed by tap-changer.

5. COMPARISON OF TAP-CHANGER WITH OTHER CUSTOM POWER TOOLS

Table 3 compares the capability of electronic tap-changer with DVR and DSTATCOM in eliminating the power quality difficulties. As seen, tap-changer with high frequency modulation is also considered. As shown in Table 3, in this simulation the high frequency electronic tap-changer operates similar to a ac/ac converter and controls the output instantaneously, it has all capabilities of DVR and DSTATCOM. It also has reasonable capabilities of eliminating sag, swell and low-frequency flickers.

6. CONCLUSIONS

This paper briefly introduced an electronic tap-changer. The capability of the distribution transformer equipped with such tap-changer in improving power quality was presented. The simulation results show that some problems such as sags, swells and voltage fluctuations can be eliminated or largely minimized by the electronic tap-changer. In addition, the performance of the electronic tap-changer compared with two custom power tools, DVR and DSTATCOM. The results indicated that the electronic tap-changer, even in the case of high frequency switching are fully comparable with other tools.

7. ACKNOWLEDGEMENTS

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