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Low Cost Dynamic Voltage Restorer

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Abstract. In this paper a low cost topology for compensation of voltage sags and swells is proposed. The dynamic voltage restorer neither uses rectifier stage nor dc capacitor and thyristors can be used as switching devices, resulting in a significant cost reduction. The control system is simple, eliminating the use of powerful computational platforms, causing also a cost reduction and reliability increase. To validate the simulation models, an experimental control platform is used to evaluate the proposed dynamic voltage restorer.

Key words

Power conditioning, Power quality, Power system restoration.

1. Introduction

Sensitive equipment and non-linear loads have become common for all consumers in sectors commercial, industrial and residential. In the past, most electrical equipment were insensitive to small supply voltage variations. Nowadays, since many industrial, commercial and even residential electrical loads have electronic logic circuits or microprocessors, they became very sensitive to voltage supply disturbances [1].

Considering this scenario, some problems about power quality can be cited mentioned: voltage sags usually caused by faults; harmonic distortions caused by non-linear loads; voltage unbalance; flickers; frequency variations.

In a general way, any disturbance in the voltage, current or frequency that results in fail or abnormal operation of an equipment can be classified as a power quality problem [1]. Studies in this subject indicate that the European Union spends around 150 billions of Euros annually due to the power quality problems, while only 297,5 millions of Euros annually are invested by companies to solve these problems [2].

Among the problems related to power quality, the voltage sags and energy interruptions represent the most frequent and significant disturbances present in the electric grid [1]. The equipment most affected by voltage sags or interruptions are the electronic devices, discharge lamps, computers and protection and control devices [1], [3]. According to IEEE Std 1159, a voltage sag is characterized as a decrease in the rms value of voltage, in one or more phases, in the range between 0.9 and 0.1 pu, with duration between half cycle and one minute [4], [5].

The Dynamic Voltage Restorer (DVR) is a device that detects the sag or swell and connects a voltage source in series with the supply voltage in such a way that the load voltage is kept inside the established tolerance limits [6], [7]. Its performance is measured in terms of the voltage that the DVR can supply, the maximum duration of the sag or swell it can compensate and the response time in which it can operate. The DVR is a controlled voltage source that produces a voltage to be applied to the system with high efficiency, low harmonics content and fast response time. Note that it is necessary to use a sophisticated control system that has a significant computational effort and the most part of the computational effort comes from the generation of the waveform that will be applied to the system.

The classical scheme of a DVR consists of an inverter connected to the grid through a transformer, as shown in Fig. 1. It can be observed a common characteristic in all topologies used in the DVR, that is the existence of a dc stage and an inverter. When a disturbance occurs, as for example a voltage sag, the DVR injects in real time compensation voltages, supplying non-disturbed voltages to the load.

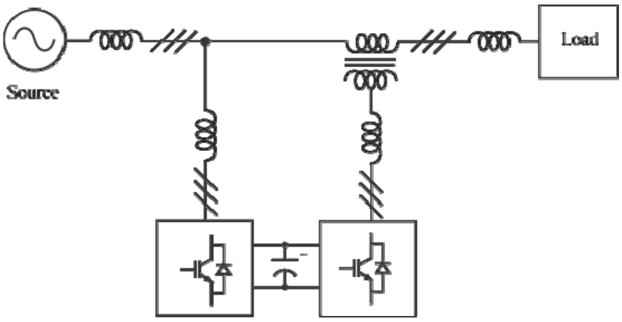

Fig. 1. Classical DVR.

It is interesting to note that in electrical systems the Total Harmonic Distortion (THD) of the supply voltages is below 5% in most cases. Therefore, it is not necessary to spend computational effort to synthesize a sinusoidal voltage that will be applied to the system if a good quality supply voltage is available. The voltage regulator uses a transformer and a tap commutator to inject the voltage needed to the system without synthesizing it, using the supply voltage itself. However, the voltage regulator has two drawbacks that do not allow the utilization as a DVR: slow response time and the need of passing through intermediate stages, i.e. it is not possible to go to tap 3 without passing through the tap 2. In this paper, a low cost DVR is proposed based on the voltage regulator principles without presenting its drawbacks

2. The Proposed Low Cost DVR

The single-phase version of the proposed scheme is seen in Fig. 2. The three-phase proposed configuration uses three single-phase sets.

A. Low Cost DVR

Observing Fig. 2, it can be seen four transformers, $T_{series1}$, $T_{series2}$, $T_{series3}$ and $T_{parallel}$. The transformers $T_{series1}$, $T_{series2}$ and $T_{series3}$ have their secondary windings connected in series with the load, with the objective of providing a voltage increment or decrement. The primary windings are connected to the switches S_{t1}, S_{t2} and S_{t3} and to the central tap of the transformer $T_{parallel}$. The switch S_{ab} selects if the voltage applied to the transformers $T_{series1}$, $T_{series2}$ and $T_{series3}$ is additive or subtractive in relation to supply voltage since $T_{parallel}$ is the feeding transformer. Note that the transformers turns ratio $T_{series1}$, $T_{series2}$ and $T_{series3}$ are 2:1, 4:1 and 8:1.

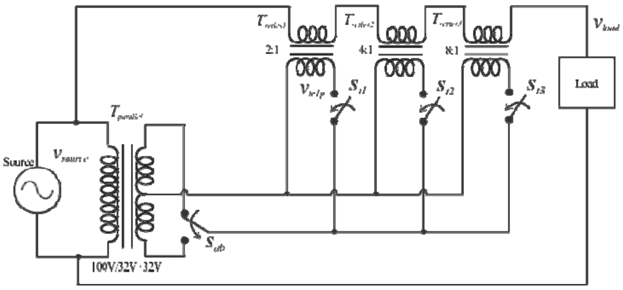

Fig. 2. Proposed scheme of the low cost DVR with three series transformers.

The load voltage is equal to the source voltage plus the DVR voltage, i. e., the sum of the secondary voltages of the series transformers. 2^{n+1}-1 different DVR voltages can be obtained through the states of the switches S_{t1}, S_{t2}, S_{t3} and S_{ab}, where n is the number of series transformers. This voltage is equal to the binary number formed by the switches states $S_{t1}S_{t2}S_{t3}$ multiplied by the minimum increment v_{tr3s}. This is very interesting since a small increment in the number of transformers results in a large increment in the number of possible states. The number of transformers to be used is a function of the number of desired states. Another important point is that there is only one transformer $T_{parallel}$ and it is the responsible for feeding the transformers of increment/decrement ($T_{series1}$, $T_{series2}$ and $T_{series3}$). For the sake of simplicity to describe the operation, four transformers are used resulting in 15 (2^4 - 1) possible states, as shown in Fig. 2.

It should be noted that if one of the switches S_{tx} (x=1,2,3) is turned-off, the corresponding transformer operates in open circuit, and considering the transformer classical model, a high impedance seen by the secondary is put in series with the load. In order to eliminate this problem, a switch with low conduction resistance can be used, in parallel with the transformer primary, as shown in Fig. 3. Analyzing Fig. 3, it can be observed that when the switch S_{tvx} is turned-on the series transformer is short-circuited and it presents a reduced impedance in the low voltage side. It is important to observe that switches S_{tx} and S_{tvx} cannot remain closed at the same time, in order to avoid short-circuiting the parallel transformer. On the other hand, switch S_{tx} must be turned on right after S_{tvx} is opened and vice-versa, since overvoltages would appear after interrupting the inductive current. Fig. 3 was redrawn to highlight the switching dependence between S_{tx} and S_{tvx}, as shown in Fig. 4.

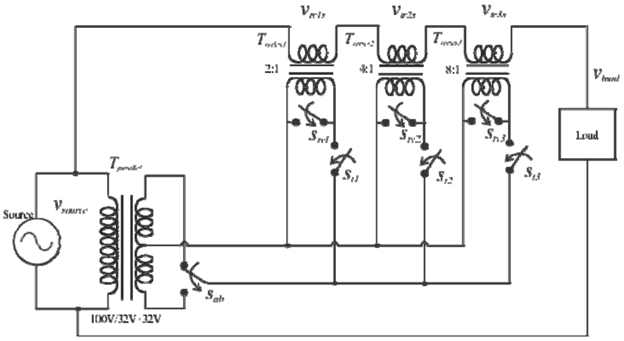

Fig. 3. DVR with two switches connected to the primary of the series transformer.

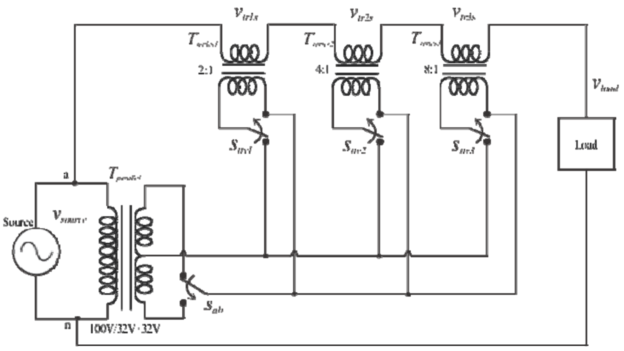

Fig. 4. DVR with one two-position switch connected to the primary of the series transformer.

The practical implementation of the bipolar switches of Fig. 4 is made as follows: each bipolar switch is composed of two bidirectional switches connected as shown in Fig. 3. The individual bidirectional switches may be implemented using a diode bridge and one IGBT or two thyristors connected in anti-parallel, as shown in Fig. 5. A snubber circuit must be carefully designed in order to avoid switches overvoltage due to interrupting inductive current (during the switches dead-time) or overcurrent due to short-circuit if both bidirectional switches remain closed (during a short non-intentional overlap-time, in which the switches could be both closed).

B. Switches States Calculation of the DVR

Considering ideal transformers and switches, the load voltage can be calculated as:

$$v_{load} = v_{source} + (v_{tr1s} + v_{tr2s} + v_{tr3s})S_{ab}, \qquad (1)$$

where S_{ab} may be equal to -1 or 1, for subtractive or additive action of the DVR, respectively, and

$$\begin{aligned} v_{tr1s} &= v_{partrs}N_{tr1}S_{t1} \\ v_{tr2s} &= v_{partrs}N_{tr2}S_{t2} \\ v_{tr3s} &= v_{partrs}N_{tr3}S_{t3}, \end{aligned} \qquad (2)$$

where v_{partrs} is the secondary parallel transformer voltage, v_{trxs} (x=1,2,3) are the series transformers secondary voltages, N_{trx} are the series transformers turns-ratios and S_{tx} are the bipolar switches states (S_{tx}=0 means the transformer short circuit and S_{tx}=1 means that the parallel transformer feeds the corresponding series transformer primary winding). Since the turns-ratios are N_{tr1}=1/2, N_{tr2}=1/4 and N_{tr3}=1/8, the following relation can be reached

$$\begin{aligned} N_{tr2} &= 2N_{tr3} \\ N_{tr1} &= 4N_{tr3}. \end{aligned} \qquad (3)$$

Using (3) the following expression can be achieved:

$$v_{load} = v_{source} + (4S_{t1} + 2S_{t2} + S_{t3})S_{ab}N_{tr3}N_{partr}v_{source}, \qquad (4)$$

where N_{partr} is the turns-ratio of the parallel transformer, i. e. $N_{partr} = v_{partrs}/v_{source}$. Analyzing 4), it can be concluded that the DVR voltage added to the available source voltage depends only on the switches states, making the device operation very simple.

For example, suppose that the supply voltage is 86.2 V, instead of 100 V (rated value). The DVR control system must determine the necessary switches states in order to compensate the voltage dip.

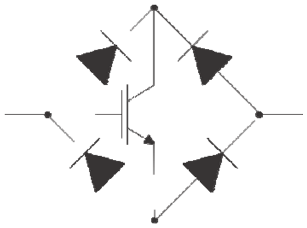

Fig. 5. Bidirectional switches in the low cost DVR.

Since an additive compensation is needed, S_{ab} must be qual to 1. Observing Fig. 2, $N_{tr3}N_{partr}$=0.04, then using (4):

$$4S_{t1} + 2S_{t2} + S_{t3} = (v_{load} - v_{source})/(0.04v_{source}) \approx 4. \qquad (5)$$

Converting the result to the binary system: $4_{10} = 100_2$. The switches states should then be $S_{t1}=1$, $S_{t2}=0$ and $S_{t3}=0$. The DVR voltage is an integer multiple of $N_{tr3}N_{partr}v_{source}$, or $0.05v_{source}$ in the example presented. This step was chosen since most utility companies allow voltage variations within (±5%) of the rated value. If a better voltage resolution is needed, more states are necessary and the number of transformers must be increased for the same maximum voltage sag compensation capability.

3. Simulation Results

The DVR proposed in Fig. 4 was simulated in MATLAB/simulink in a 220 V grid. Situations with three-phase (type A) and single-phase (type B) faults were tested in the system [1]. The faults occur between 100 and 200 ms. Figs. 6 and 7 show the performance of the proposed DVR for three-phase and single-phase faults, respectively. The proposed low cost DVR is capable of compensating both balanced and unbalanced voltage sags.

4. Experimental Results

An experimental control platform was used to evaluate and validate the proposed DVR. The control uses a reference voltage of 100 V, compensation step of 5%, seven steps of compensation and tolerance of 5%. In the experimental results, channel 1 shows the the grid voltage and channels 2, 3 and 4 show the switches states of the lowest, medium and highest power transformers, respectively.

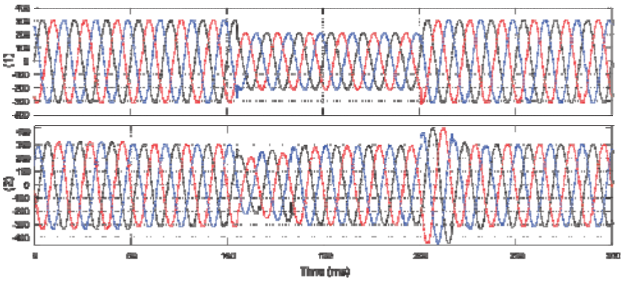

Fig. 6. Voltages (V) - (1) grid and (2) load: type A.

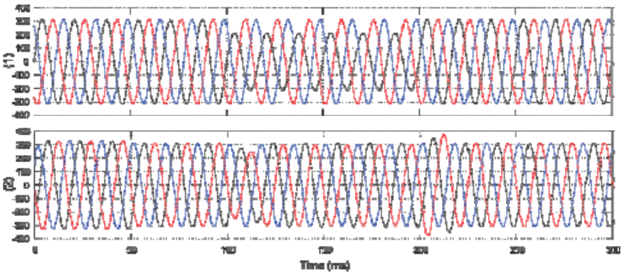

Fig. 7. Voltages (V) - (1) grid and (2) load: type B.

In Fig. 8, point A indicates when the voltage sag begins with voltage of 95%. The control response takes around 11 ms (channel 2), according to the design and simulations. The voltage sag ends in point B and the control evolves progressively until the rms voltage value (channel 1) attends the value allowed in the standard. In this example, state 4 (channel 4 in high level) is the right option to correct the fault. Point C indicates where a voltage swell begins, but there is no state change due to tolerance limit. In the next cycle, the limit is crossed and the control reacts, changing the state. Point D represents the end of the voltage swell. The grid voltage goes back to the allowable range and the control does not execute any action.

In Fig. 9, point A indicates the moment when a voltage swell begins with voltage of 112%. Observe that the control is adjusted for tolerance of 5%. Therefore, the states change until the limit (seven steps) without achieving the correct compensation in this case. However, the proposed topology can supply perfectly the voltage value to be injected for most cases in practical applications and this example is only to show that there are some cases in which the low cost DVR will not compensate the voltage to the right value.

5. Comparison: Classical and Low Cost DVR

The comparison is based on the following aspects:

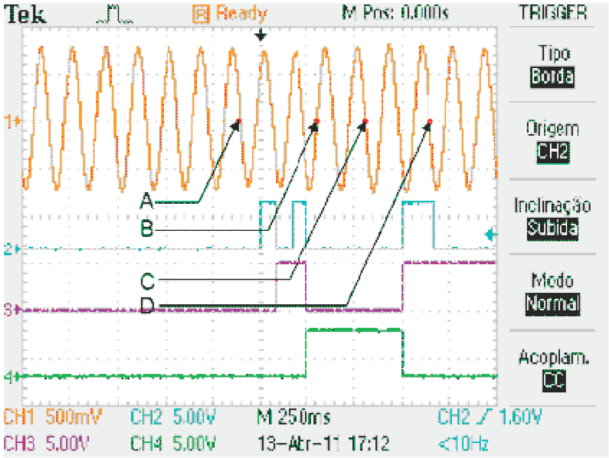

Fig. 8. Control of DVR: voltage sag followed by voltage swell.

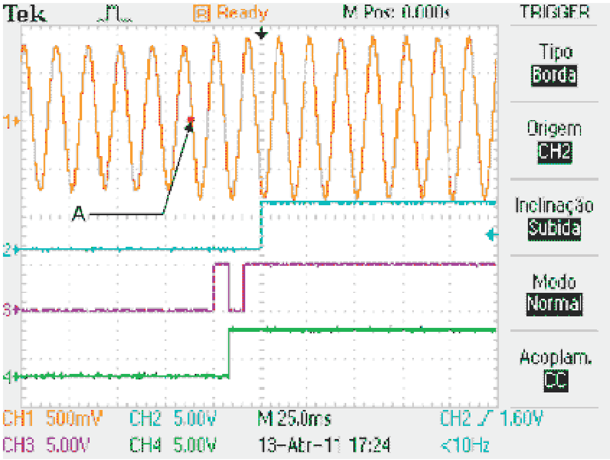

Fig. 9. Control of DVR: non-compensable voltage swell.

A. Maximum fault magnitude for correct compensation;
B. Ability to compensate phase-angle displacement;
C. Maximum fault duration for correct compensation;
D. Response time;
E. Harmonic production;
F. Total cost.

The evaluation results can be summarized in Table I. The performance of one topology in relation to the other is considered by using "+" and "-" for better and worse quality, respectively. However, there are some cases that both topologies attend the standards.

A. Maximum fault magnitude for correct compensation

The proposed DVR (Fig. 4) presents good results in case of single-phase (types B and D) and three-phase (type A) voltage sags, but it only attenuates two-phase voltage sags (types C and E). On the other hand, the classical DVR (Fig. 1) compensates any voltage sag with the same performance. However, it is important to mention that almost all voltage sags are single-phase. Therefore, the proposed topology can supply the correct voltage value to be injected for most cases in practical applications.

B. Ability to compensate phase-angle displacement

For single-phase faults that result in phase-angle displacement (voltage sag type D), the proposed topology does not have an effective compensation of displacement, but the load voltage magnitude is compensated.

C. Maximum fault duration for correct compensation

In the classical DVR, if the converter responsible for controlling the dc link voltage is connected in parallel with the load, then there is no limitation about the compensation time. This is not the case for the usual topologies in which the converter responsible for controlling the dc bus voltage is connected at the point of connection voltage. The proposed DVR does not have dc link and consequently there is no limitation about compensation time.

D. Response time

The voltage sag is characterized as a decrease in the rms voltage, in one or more phases, in the range between 0.9 and 0.1 pu, with duration between half cycle and one minute. According to the requisites imposed by CBEMA curves and PRODIST, the DVR does not need to have a response time lower than one cycle. Both topologies obey the criteria imposed by the technical standards in terms of response time.

E. Harmonic production

There is no harmonic production in the proposed DVR during the steady state operation.

Table I. - DVR Comparison: classical x proposed

Criterion	A	B	C	D	E	F
Proposed	+	-	+	+	+	+
Classical	+	+	+	+	-	-

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The switching losses are minimal, occurring only when change in the switching state is needed.

F. Total cost

The classical DVR is composed of two voltage source converters, one having six diodes and the other with eight IGBTs with eight diodes in anti-parallel (in order to allow imposing zero-sequence components for compensating single-phase faults). There is also a high cost dc capacitor between the two converters. The proposed DVR does not use rectifier stage nor dc capacitor and thyristors can be used as switching devices, resulting in a significant cost reduction. The switching occurs only when a change in the switching state is needed, increasing the efficiency and avoiding expensive heat sinks. The control system is very simple, eliminating the need of powerful computational platforms, causing a cost reduction and reliability increase.

6. Cost Analysis

For cost comparison, the average costs of the main components used in both topologies (Figs. 1 and 4) are listed, considering two devices designed to attend the same load with the same voltage level.

Only the cost of the necessary components for building the DVRs are considered in the comparison due to difficulty of measuring other associated costs.

The design parameters are: voltage source - 13.8 kV; load power - 1 MVA; three-phase voltage sag - 35\%; single-phase voltage sag - 50\%; unity power factor; compensation time - 1 s.

The load current is calculated by:

$$I = S/(3^{1/2}E), \tag{6}$$

where I is the rms current in A, S is the apparent power in VA and E is the rms voltage in V. Applying (6) to the design data, a current of 41.83 A is obtained. This is the current that flows through the secondary windings of the coupling (classical DVR) and the increment/decrement (low cost DVR) transformers.

A. Classical DVR

As the desired compensation level for the single-phase load is 50% (worst compensation case), the power of the coupling transformer used in the classical DVR is calculated as:

$$S_{ta} = S{\cdot}N_c/3 = 0.5{\cdot}1000/3 = 166{,}67 \text{ kVA}, \tag{7}$$

where S_{ta} is the apparent power of the single-phase coupling transformer, S is the load apparent power and N_c is the compensation level of voltage sag.

The secondary voltage of the coupling transformer can be calculated by multiplying the load single-phase voltage by the desired compensation level. Therefore, the secondary voltage is 3,983.7 V. Considering the turns-ratio 1:1 for the coupling transformer, the minimal dc link voltage can be calculated as:

$$V_m = V_s\, 3^{1/2} 2^{1/2} = 9{,}756.8 \text{ V}, \tag{8}$$

where V_m is the minimal dc link voltage and V_s is the secondary voltage of the coupling transformer.

Knowing the minimal dc link voltage, it is possible to calculate the capacitor value by defining the remaining energy available in the dc link. The lowest possible remaining energy would be the logical choice since it determines the capacitor value, but this would result in a high steady state voltage (voltage in which the DVR does not inject neither absorb energy), impacting directly in the rated voltage and cost of the switches. The remaining energy of 1 MJ was chosen for this comparison. The capacitor value is calculated as:

$$C = 2E_m/V_m^2 = 21 \text{ mF}. \tag{9}$$

The steady state and the maximum dc link voltages can be calculated by using

$$V = (2E/C)^{1/2}. \tag{10}$$

As the capacitor injects 350 kJ until reaching the minimal voltage and absorbs 350 kJ until reaching the maximal voltage, the steady state and the maximum dc link voltages are, respectively:

$$\begin{aligned} V_t &= (2{\cdot}1350000/\,0.021)^{1/2} = 11{,}338.9 \text{ V} \\ V_m &= (2{\cdot}1700000/\,0.021)^{1/2} = 12{,}724.2 \text{ V}. \end{aligned} \tag{11}$$

Considering the rated voltage of the switches in function of the market available and price, IGBTs of 1,700 V are chosen. Therefore, it is necessary to reduce the maximum dc link voltage, fitting the switches voltages. Adopting a safety margin of 33%, the same margin used in commercial inverters, the maximum dc link voltage has to be reduced to 1,139 V. To obtain the desired reduction, the turns-ratio of the coupling transformer is 1:12 and its primary voltage is 332 V. To calculate the current through the IGBTs, the primary current is multiplied by the turns-ratio, obtaining 502 A.

The coupling transformer has secondary voltage of 3,983.7 V, primary voltage of 332 V and rated power of 333 kVA. The power is defined as double of the power that will be injected by the transformer. This is a safety margin used by the industry with the objective of avoiding saturation in transient situations that would cause damage to the DVR [8]. Another important characteristic is the low resistance in the windings to minimize losses. Note that this transformer presents special characteristics and it is designed to attend the application requirements, resulting in high cost. The price of the coupling transformer in relation to the conventional transformer is increased in 10% due to impossibility of obtaining the exact cost for the comparison. The cost incorporates the filter that constitutes other element in which the characteristics depend on the place where it will be used.

Table II shows all considered elements and the calculated final cost. Table II was built by using the prices obtained in [9] and considering the average price of the conventional single-phase and three-phase transformers of US$ 25.41/kVA and US$ 63.53/kVA, respectively.

B. Low Cost DVR

The proposed DVR shown in Fig. 4 has 15 states. The power of the lowest increment/decrement transformer is calculated as:

$$S_{id} = S\cdot N_c / [3\cdot(2^n-1)] = 23.81 \text{ kVA}, \qquad (12)$$

where n is the number of increment/decrement transformers.

The powers of the other transformers are 47.62 kVA and 95.24 kVA and the sum of powers of the increment/decrement transformers results in the same power of the coupling transformer in the classical DVR.

The rated voltage of the thyristors was chosen as 1,800 V, similar to the IGBTs voltages in the classical DVR, but any other voltage level could be selected. This choice results in rms voltage of 1,145.5 V considering the safety margin of 33%, as in the classical DVR.

The currents in the primary windings (also in the thyristors) of each increment/decrement transformer can be calculated as:

$$\begin{gathered} I = S/E \\ I_1 = 95{,}240/1145.5 = 83.14 \text{ A} \qquad (13) \\ I_2 = 47{,}620/1145.5 = 41.57 \text{ A} \\ I_3 = 23{,}810/1145.5 = 20.78 \text{ A} \end{gathered}$$

The currents in the thyristors used in the supplying transformer can be calculated by using (6):

$$I_a = 350{,}000/(1145.5\cdot 3^{1/2}) = 101.85 \text{ A} \qquad (14)$$

Table III shows the calculated costs for the proposed DVR. Comparing tables II and III, it can be verified that the calculated cost of the proposed DVR is 54.7% of the calculated cost of the traditional DVR.

Table II. - Calculated cost of the classical DVR

Item	Price (US$)
Switches	2,288.00
Heat sink and accessories	389.39
Three-phase rectifier	1,549.48
Transformer 13.8kV/939V,300kVA	19,059.92
Capacitors bank	6,670.11
Coupling transformers	37,273.09
Total	67,229.99

Table III. - Calculated cost of the low cost DVR

Item	Price (US$)
Switches	1,274.43
Heat sink and accessories	735.56
Three-phase rectifier	1,549.48
Transformer 13.8kV/1.146kV,350kVA	22,236.34
Increment/decrement transformers	12,706.73
Total	36,778.79

7. Conclusion

In this paper, a low cost dynamic voltage restorer is proposed for application in three-phase systems. The proposed topology is very attractive because the traditional dynamic voltage restorer has not been used in power systems applications due to high cost of its components. A comparative analysis between the proposed and classical dynamic voltage restorers is done and simulation results show that the low cost topology presents a better cost-benefit solution in relation to the traditional topology. Experimental results of the control system of the proposed topology are also presented.

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