



Mitigation of Transient Recovery Voltages using the Supercapacitor

Eman Awad and Ebrahim A. Badran

KEYWORDS:

TRV, Supercapacitor, re-ignition, restrike, RRRV, ATP/EMTP

Abstract— This paper investigates the use of supercapacitor to mitigate the transient recovery voltage (TRV) in a simple power system. The TRV concept and the phenomena surround its occurrence such as re-ignition and restrike are represented. Also, the different waveshapes of TRV are evaluated. The effect of energizing different power system parameters, such as resistance and capacitance, resulting in TRV is evaluated. At first, the effect of energizing three different values of a damping resistance, one by one, is studied. Then, the influences of energizing of a capacitor, with three different values, on the tested system are illustrated. Finally, the effect of combining different values of the damping resistance and the capacitance are evaluated. The effect of using supercapacitor as TRV mitigation method is studied. Alternating transient program (ATP/EMTP) is used to simulate the test system and the proposed supercapacitor-based method. The simulation results ensure the validity of the proposed method.

I. INTRODUCTION

SUPERCAPACITORS have higher power density, faster dynamic response, and longer cycle life comparing with other energy storage devices such as batteries. Therefore, the applications in which the supercapacitor is used expanded to include wireless sensor networks, biomedical devices, electric and hybrid vehicles, and smart grid [1-3].

When a switching action occurs on a system, a substantial short circuit current usually flows. Therefore, the switching device starts to open; the parting of the circuit breaker contacts does not in itself interrupt the current. An arc will established between the parting contacts, through which the current will continue to flow. The arc across the contacts will continue until the current approaches zero. At current zero the arc will distinguish and the Transient Recovery Voltage (TRV) will appear across the open contacts. TRV is the voltage appearing

across the contacts of circuit breaker following current zero when a switching action occurs [4, 5].

When a capacitor is energized, TRV can be as high as 2 pu at the capacitor location. The magnitude of TRV can be reduced by adding a damping resistance to the system [6-8].

Alternating transient program (ATP) is usually used to compute the TRV waveforms and to calculate its parameters. ATP is a computer program that allows an electrical system to be modeled and analyzed in the time domain, referred to as the electromagnetic transients program (EMTP). The program solves the system equations numerically in the time domain and the values of the TRV are determined for specific time instants within a user-specified simulation time [9, 10].

This paper investigates the use of supercapacitor to mitigate the TRV in a simple power system. The TRV concept and the phenomena surround its occurrence such as re-ignition and restrike are represented. Also, the different waveshapes of TRV are evaluated. The effect of energizing different power system

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Corresponding Author: Eman Awad, Mansoura university, Faculty of Engineering, Electrical Engineering Department. (E-mail: eman_sk2008@yahoo.com).

Ebrahim A. Badran, Mansoura university, Faculty of Engineering, Electrical Engineering Department. (E-mail: ebadran@hotmail.com).

parameters, such as resistance and capacitance, resulting in TRV is evaluated. At first, the effect of energizing three different values of a damping resistance, one by one, is studied. Then, the influences of energizing of a capacitor, with three different values, on the tested system are illustrated. Finally, the effect of combining different values of the damping resistance and the capacitance are evaluated. The effect of using supercapacitor as TRV mitigation method is studied. ATP/EMTP is used to simulate the test system and the proposed supercapacitor-based method. The simulation results ensure the validity of the proposed method.

II. TRANSIENT RECOVERY VOLTAGE

A. Transient Recovery Voltage Concepts

The circuit breaker contacts movements have influence on TRV, as it caused the insulation gap stress and arcing in the interrupting medium [10, 11]. Following current extinction, the interrupting media is trying to return from a conduction state to an insulator state [12, 13]. But the attempting of the interrupting media to become a good insulator is incompatible with the increasing TRV [13, 14].

If the insulation recovers more quickly more than the TRV, after less than half cycle of power frequency, a successful interruption occurs, it is referred to as reigniting. Reigniting generally occurs almost immediately after the current zero, because the arc plasma containing conducting ions re-establishes current [13, 15].

However, if the interruption process is repeated more than one time. The interruption process continues until successful interruption occurs or until the breaker fails, it is designated a restrike [13].

Restrikes are really dielectric breakdowns and can occur anytime during the TRV cycle, although usually they are associated with breakdowns later in the cycle (say tens to hundreds of microseconds) when the TRV has sufficiently high magnitude. Such an event is akin to a lightning flash-over across an insulator [10, 16].

B. Transient Recovery Voltage Waveshapes

TRV have different waveshapes, the four categories given are listed based on increasing on rate of rise of recovery voltage (RRRV) [15].

1. Exponential (over-damped) TRV Waveshape.

The waveshape is obtained from a circuit breaker interrupts a switching action at its terminals in a well-developed substation which include step up and/or step-down transformers and a large number of transmission lines and/or underground cable [13, 15].

At higher short circuit currents which are associated with the transmission network, the TRV is less influenced by the natural power frequency. The RRRV, within the range of 0.5 to 3.5 kV/ μ Sec, tends to decrease when the short circuit current increases [15, 17].

2. Oscillatory (Under-damped) TRV Waveshape.

The oscillatory TRV occurs generally when a switching action is limited by transformer or reactor and no transmission

network is present to provide damping [17].

Even when a transmission network is presented it is possible for TRV to be oscillatory. When, the short circuit current is generally low (30% of rated short circuit current) due to the low number of transmission lines connected to the system. Also, to be oscillatory, the surge impedance of a source sideline has to be equal or higher than $0.5\sqrt{L_{eq}/C_{eq}}$ whereas; L_{eq} , and C_{eq} are equivalent source inductance and capacitance, respectively [13, 17].

The frequencies associated with oscillatory TRV tend to be in the range of 1 kHz to 100 kHz. The highest frequencies generally occur on the lowest voltage systems and the lowest frequencies on the highest voltage systems [15].

3. Triangular (Sawtooth) TRV Waveshape.

Sawtooth TRV is characterized by high RRRV. The RRRV of the triangular shape is mainly determined by the line surge impedance. The RRRV for this type of TRV is higher than exponential or oscillatory TRVs, however, the TRV peak is generally lower. These are seen more severe to circuit breakers because of high RRRV even though the peak of TRV is less [13, 17].

Even for any other type of TRV waveshapes, there is a small triangular characteristic at the beginning of the waveshape. This portion of the wave is referred to as the initial TRV and results from reflections on the bus work in the substation [15].

The closer the switching action is to the circuit breaker, the higher the RRRV of the initial TRV due to the higher short circuit current, while the crest magnitude of the triangular wave decrease due to the shorter time for the reflected wave to return [17].

III. TRV EFFECT ON A SIMPLE POWER SYSTEM: CASE STUDY

The effect of various power system parameters on TRV at a simple power system is investigated using ATP. At first, ATP is used to simulate the switching action and the resulting in TRV is evaluated. The simulation results are compared with a published one [18, 19] for the same system data. Then, the effects of various power system parameters are discussed.

A. Simulation of TRV Using ATP

ATP is used to simulate a simple power system which consists of a voltage source, source impedance, vacuum circuit breaker, and a damping RC branch, which is added in parallel with the circuit breaker.

The tested power system and ATP model are illustrated in Fig. 1 (a) and (b), respectively. The parameters of the tested power system are given in Table 1.

Fig. 2 shows a comparison between the published results in [18, 19] and ATP simulation results for the TRV which appears at the circuit breaker contacts after the current interruption.

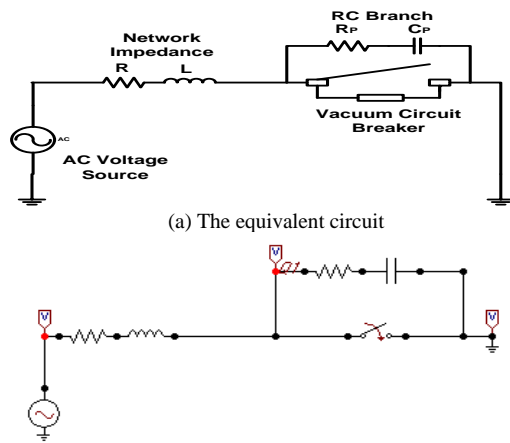


Fig. 1: The test power system.

Table 1
The Tested Power System Model Data [21].

Parameter	Value
Equivalent network resistance (R)	0.1 Ω
Equivalent network inductance (L)	2 mH
Resistance of RC branch (Rp)	200 Ω
Capacitance of RC branch (Cp)	85 nF
Maximum phase voltage (Vmax)	33 kV

Fig 2 (a) show the published results from [18, 19]. The published results are simulated by ATP program (blue line) and mathematically analysed (red points). As a confidence test for ATP, a comparison between the published results and ATP simulation results.

By comparing the published results with the simulated one, the results are found to be close. Referring to Fig 2 (b), the TRV is increased to the maximum phase voltage from 33 kV (red line) to 40.5 kV with rise time (T_r) equals 29.5 μs (blue line).

B. Effect of Single Power System Parameter on TRV

As mentioned before, the nature of the circuit being interrupted affects the TRV waveshape. Therefore, the effect of using various parameters for the damping RC branch is studied.

The damping RC branch is added in parallel with the circuit breaker because of the higher RRRV of the TRV since the tested power system has inductive characteristics.

The effect of using different values of the resistance (R_p) or the capacitance (C_p) is evaluated. The values of the other system components such as network impedance are kept constant.

For the first case, three different values of R_p are represented. At the beginning, R_p is 200 Ω, then the value of R_p is changed to 100 Ω. Finally, the value of R_p is changed to 2000 Ω. Fig. 3 (a) shows The TRV appears at the circuit breaker contacts for the three different values of R_p .

The results show that, for $R_p = 200 \Omega$, the maximum TRV is 40.5 kV with T_r equals to 29.5 μs. However, for $R_p = 100 \Omega$, TRV reaches 40 kV with T_r equals to 64.45 μs. For $R_p = 2000 \Omega$, the maximum TRV is 33 kV with T_r equals to 4.6 μs.

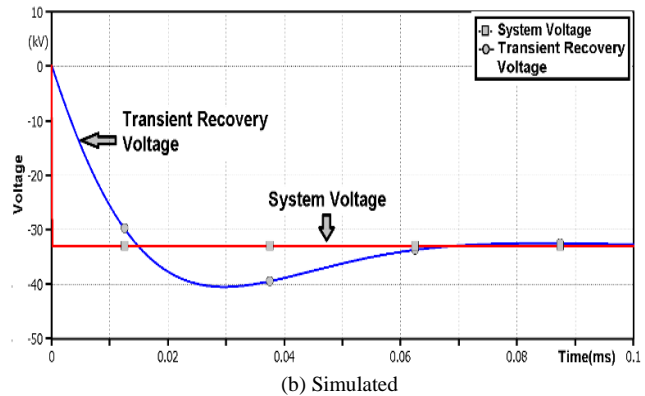
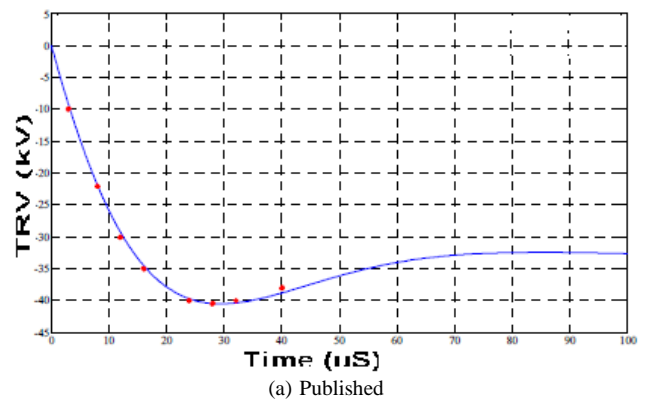


Fig. 2: The TRV Appears at the Circuit Breaker Contacts After Current Interruption.

It can be seen that the increasing of the resistance of the damping RC branch reduces the TRV amplitude and its rise time. For the highest tested value of R_p ($R_p = 2000 \Omega$) the TRV reduces to reach values close to its rated values.

For the second case, three different values of C_p of the damping RC branch are represented. At the beginning, C_p equals 85 nF, then the value of C_p changes to 85 pF, and finally, the value of C_p is increased to 85 μF. Fig. 6(b) shows the TRV appears at the circuit breaker contacts for the three different values of C_p of the damping RC branch.

The results show that, the maximum TRV is 63.64 kV with T_r equals to 1.3 μs for $C_p = 85 \text{ pF}$ compared with 40.5 kV with T_r equals to 29.5 μs for $C_p = 85 \text{ nF}$. The most reduced value of TRV are 32.5 kV with T_r equals 42 μs for $C_p = 85 \mu\text{F}$.

From the results, when the capacitance of the damping RC branch increase the TRV amplitude is reduces, however the TRV rise time is still above the acceptable limits. For $C_p = 85 \mu\text{F}$, the highest test value, the TRV is reduced to reach value close to the rated voltage value.

On the contrary, the reduction of the capacitance of the damping RC branch increases the TRV amplitude and creates an oscillatory TRV waveshape. This can be attributed to the absence of any devices can causes damping, such as transformer or transmission line, in the tested system.

Table 2 summarized the effect of using different values of the resistance or the capacitance of the damping RC branch on TRV amplitude and rise time.

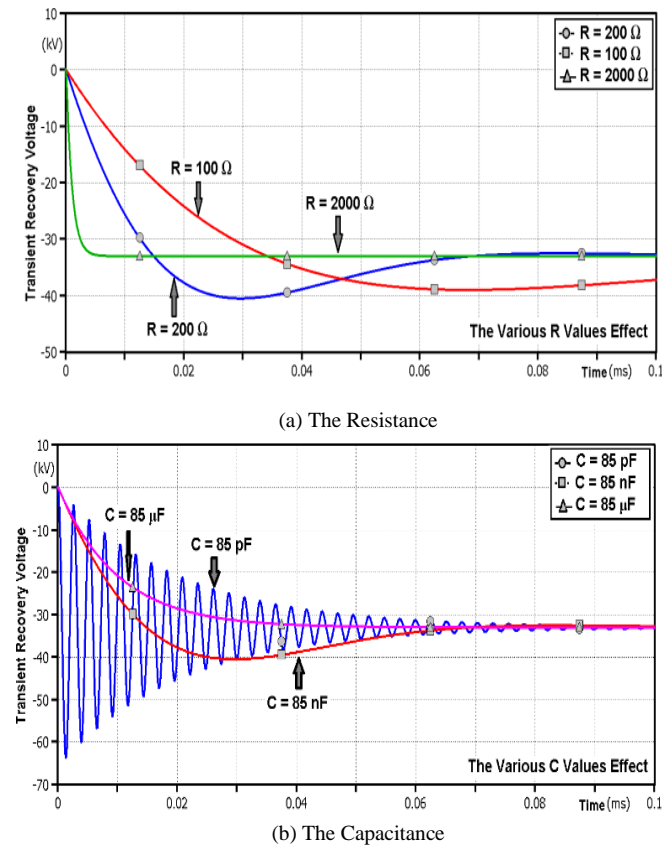


Fig. 3: The TRV at the Circuit Breaker Contacts for Different Values of the Damping RC Branch Parameters.

TABLE 2

The Effect of Using Different Values of the Resistance or the Capacitance of the Damping RC Branch on TRV.

Component	Values	TRV (kV)	Rise Time (μ s)
Resistance	$R_p = 100 \Omega$	40	64.4
	$R_p = 200 \Omega$	40.5	29.5
	$R_p = 2000 \Omega$	33	4.6
Capacitance	$C_p = 85 \text{ pF}$	63.64	1.3
	$C_p = 85 \text{ nF}$	40.5	29.5
	$C_p = 85 \mu\text{F}$	32.5	42

C. Effect of Mixed Power System Parameters on TRV

The magnitude of the TRV normally does not depend directly on any single parameter and a variation of one parameter can often alter the influence of another parameter. Therefore, studying the combination between the various system parameters is important.

The effect of using different values of the damping RC branch parameters, R_p and C_p , is evaluated. The values of the other system component such as network impedance are kept constant.

Four different cases are studied, in this subsection, with two different values of each parameter.

For the first case, R_p equals 100Ω , and the value of C_p is 85 pF . This case is a combination of the smallest test values of these parameters, in this study.

At the second case, a combination of the highest test values of the damping RC branch parameters is discussed. Therefore, the value of R_p is 2000Ω , and C_p equals $85 \mu\text{F}$.

For the third case, the smallest test value of R_p is combined

with the highest test value of C_p , Therefore, the value of R_p equals 100Ω , and C_p is $85 \mu\text{F}$. Finally, a combination of the highest test value of R_p and the smallest test value of C_p is studied. Therefore, at the fourth case, the value of R_p equals 2000Ω , and C_p is 85 pF .

Fig. 4 shows the effect of using different values of the damping RC branch parameters on TRV which appears at the circuit breaker contacts.

Using a combination of the smallest tested values of R_p and C_p , for the first case increases the TRV amplitude with transient behaviour and sawtooth TRV waveshape.

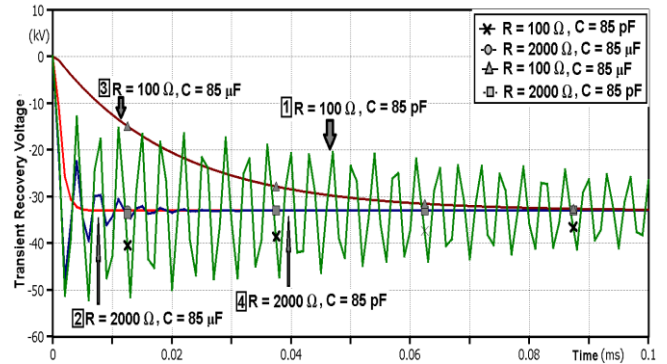


Fig. 4: The Effect of Using Different Values of the Damping RC Branch Parameters on TRV Appears at the Circuit Breaker Contacts.

However, at the second case, with the combination of the highest test values of the damping RC branch parameters, both of the TRV amplitude and TRV rise time are reduced.

For the third case, using the smallest test value of R_p with the highest test value of C_p results in a reduction of the TRV amplitude; however their rise time is not reduced.

Finally, for the fourth case, the combination of the highest tested value of R_p and the smallest tested value of C_p results in a reduction of the TRV amplitude but it takes time to reach the rated voltage values due to the existence of initial TRV.

The first case and the third case do not live up to the required results. Because one of the TRV main characteristics, the TRV amplitude or the TRV rise time, are not reduced in both cases.

The second case and the third case concluded that using the highest test value of R_p results in the reduction of the TRV amplitude. And using the highest test value of C_p results in the reduction of the TRV rising time.

So, the combination of the highest tested values of the damping RC branch parameters, at the second case, is the best case scenario. Table 3 summarized the effect of using different values of the damping RC branch parameters on the TRV.

TABLE 3

The Effect of Using Different Values of the Damping RC Branch Parameters on TRV.

Case	Resistance Values	Capacitance Values	TRV (kV)	Rise Time (μ s)
First	$R_p = 100 \Omega$	$C_p = 85 \text{ pF}$	52.12	2
Second	$R_p = 2000 \Omega$	$C_p = 85 \mu\text{F}$	33	9
Third	$R_p = 100 \Omega$	$C_p = 85 \mu\text{F}$	32.8	99
Fourth	$R_p = 2000 \Omega$	$C_p = 85 \text{ pF}$	33.02	34

IV. MITIGATION OF TRV USING SUPERCAPACITOR

In this section, the effect of using supercapacitor as TRV

mitigation method is studied. Changing the resistance and the capacitance of the simple power system is found to be effective on TRV mitigation. Replacing the damping branch capacitance with a supercapacitor looks like a step worth studying.

Taking the advantage of the supercapacitor installation at power systems and using it as a transient mitigation method is a new trend in transient analysis studies [20].

A. Modeling of Supercapacitor-Based Mitigation Method

There are many models and equivalent circuits introduced in the literatures for supercapacitor. The parameters of the supercapacitor-based mitigation method include capacitance (C), equivalent series resistance (R_S), and equivalent parallel resistance (R_m) [21, 22].

The equivalent series resistance (R_S) is usually describes internal resistance of the supercapacitor. R_S is almost in the range of 100 milliohms to 10 ohms but influences the energy efficiency and power density [7, 23].

The equivalent series resistance (R_S) for the proposed supercapacitor-based mitigation method is given by:

$$R_S = V_c^2 / (4 \times P_{max}) \tag{1}$$

where P_{max} is the maximum dischargeable power, and V_c is the average voltage across the capacitor [23].

The capacitance C of the supercapacitor-based mitigation method can be expressed by:

$$C = (2 \times E) / V_{SC}^2 \tag{2}$$

where V_{SC} is the supercapacitor rated voltage, and E energy storage capacity.

The equivalent parallel resistance (R_m) is in the range of several kilo-ohms and decides the leakage current when the supercapacitor is in a standby mode [22, 23]. The parameters of the supercapacitor-based mitigation method model are given in Table 4.

B. The Supercapacitor-Based Mitigation Method Effect on TRV at Single Phase System

The effectiveness of the supercapacitor as TRV mitigation method is studied. The switching operations are applied at t=0.0001s. The parameters of the test power system are given in Table 1. The supercapacitor replaced C_p in the damping RC branch. Meanwhile, R_p is replaced by a damping resistance equals 2000 Ω.

The tested power system after adding the supercapacitor and the damping resistance are illustrated in Fig. 5

Fig. 6 shows the effect of using the supercapacitor with and without damping resistance on TRV appears at the circuit breaker contacts.

Due to the switching operation, the TRV is increase to 40.5 kV with T_r equals 29.5 μs from its steady state voltage. Using the supercapacitor without damping resistance, the maximum TRV is decreased to the steady state values with T_r equals 63 μs. By adding the damping resistance to the supercapacitor, the maximum TRV is decreased to the steady state values with T_r equals 6 μs.

From the simulation results, it is shown that the supercapacitor has a good effect with the damping resistor for the TRV mitigation.

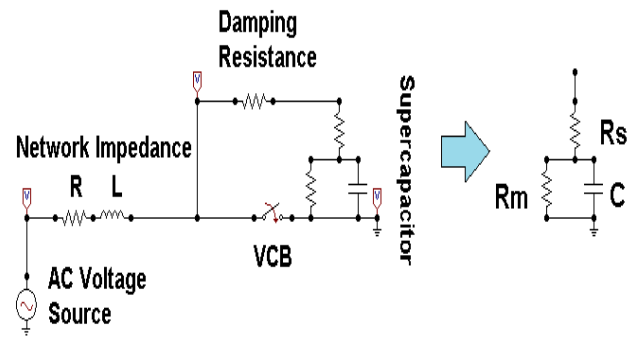


Fig. 5: The ATP Model of the Test Power System with the Supercapacitor and the Damping Resistance.

TABLE 4
THE PROPOSED SUPERCAPACITOR -BASED MITIGATION METHOD MODEL DATA

Parameter	Value	Parameter	Value	Parameter	Value
R _S	0.35 Ω	C	22 mF	R _P	2 kΩ

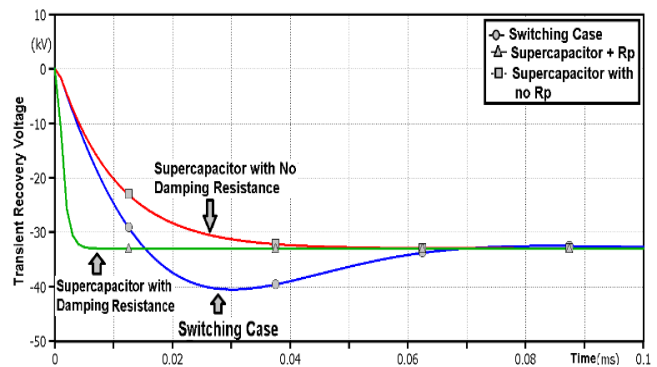


Fig. 6: The Effect of using the Supercapacitor with and without Damping Resistance on TRV.

VI. CONCLUSION

In this paper, the TRV is mitigated using a supercapacitor-based mitigation method in a simple power system. The TRV concept and the phenomena surround its occurrence such as re-ignition and restrike are represented. Also, the different waveshapes of TRV are evaluated. The effect of various power system parameters on TRV at the tested power system is investigated using ATP/EMTP.

From the simulation results, it can be concluded that the increasing of the resistive component in the test system reduces the TRV characteristics to ideal values. However, increasing the capacitive component in the test system reduces the TRV values; however their rise time is not reduced.

A Combination of the highest values of the resistive and capacitive components in the test system results in the reduction of the TRV. However, the increasing of the capacitance value is an issue.

Therefore, a supercapacitor-based mitigation method is proposed and tested. The results show that the supercapacitor has a good effect with the damping resistor for the TRV mitigation.

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Title Arabic:

أخام جهود الاسترداد العابرة باستخدام المكثف الفائق

Arabic Abstract:

يشرح البحث استخدام المكثفات الفائقة لأخام جهد الاسترداد العابر (TRV) في نظام طاقة بسيط. في البداية تم استعراض مفهوم جهد الاسترداد العابر والظواهر المحيطة بحدوثه مثل إعادة الاشتعال والاستعادة. كما تم تقديم الأشكال المختلفة لموجات جهد الاسترداد العابر. تم دراسة تأثير عناصر النظام الكهربائي، مثل المقاومة والسعة على جهد الاسترداد العابر. أولاً تم دراسة تأثير ثلاث قيم مختلفة لمقاومة الأخماد، واحدة تلو الأخرى. و بعد ذلك، تم تفعيل النظام المختبر مع تغير سعته الكهربائية باستخدام ثلاث قيم مختلفة لمكثف و دراسة مدى تأثيره بذلك. أخيراً تم دراسة تفعيل النظام المختبر على قيم جهد الاسترداد العابر مع الجمع بين قيم مختلفة لمقاومة الأخماد والسعة الكهربائية. ثم تم تقديم مقترح باستخدام مكثف فائق لأخام جهود الاسترداد العابرة الناتجة عن عمليات تفعيل عناصر النظام المختبر. تم استخدام برنامج حساب الظواهر الكهرومغناطيسية العابرة (ATP / EMTP) لمحاكاة النظام المختبر والمكثف الفائق المقترح كطريقة لأخام جهود الاسترداد العابرة. وقد اوضحت نتائج البحث فاعلية استخدام المكثف الفائق كطريقة لأخام جهود الاسترداد العابرة.