World Academy of Science, Engineering and Technology
International Journal of Electrical and Computer Engineering
Vol:4, No:3, 2010

Surge Protection of Power Supply used for Automation Devices in Power Distribution System

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Abstract—The intent of this essay is to evaluate the effectiveness of surge suppressor aimed at power supply used for automation devices in power distribution system which is consist of MOV and T type low-pass filter. Books, journal articles and e-sources related to surge protection of power supply used for automation devices in power distribution system were consulted, and the useful information was organized, analyzed and developed into five parts: characteristics of surge wave, protection against surge wave, impedance characteristics of target, using Matlab to simulate circuit response after 5kV,1.2/50s surge wave and suggestions for surge protection. The results indicate that various types of load situation have great impact on the effectiveness of surge protective device. Therefore, type and parameters of surge protective device need to be carefully selected, and load matching is also vital to be concerned.

Keywords—automation devices in power distribution system, MOV, surge, T type low-pass filter.

Open Science Index, Electrical and Computer Engineering Vol:4, No:3, 2010 publications.waset.org/7767.pdf

I. Introduction

WITH fast development of automatic power distribution technology, more and more electronic devices are used in the power distribution system for protection and monitoring purpose. The electromagnetism environment is much more complex than normal application because most control objects of these electronics are of high voltage and heavy current devices. Magnetic disturbance, static and harmonics interference caused by heavy current, lightning and non linear ferromagnetic components respectively are commonly existed in such system. Those interferences may have negative effect on reliability of electronic devices used in the power distribution system. In some server cases, it may result in critical damage to devices used in power distribution system such as generator and transformers. According to research done by Lightning Protection Office of State Meteorological Administration, more than seventy per cent electrical power accidents are caused by thunderstorm and lightning propagated from power wire[1]. The essay is meant to examine surge wave characteristics and give suggestions for power system surge protection and surge suppressor.

II. Characteristics of lightning wave

According to IEC criteria lightning wave is expressed by 1.2/50μs or 8/20μs surge wave commonly, which are two different forms of the same surge wave in the case of open circuit and short circuit respectively [2]. Two surge waves can both simulate lightning realistically because the consequence of simulated lightning wave has characters of steep rise and high amplitude, which pose great threaten to power supply of electronics devices. At the same time, the open circuit voltage is well defined as 5kV or 1kV by the criteria [2]. Therefore, 1.2/50μs surge wave, whose value is 5kV, is adopted as lightning wave expression in this essay.

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A. Mathematical model of surge wave[3]

1.2/50μs surge wave model is given by double exponential function

$$V(t) = AV_p(1 - e^{-\frac{t}{\tau_1}})e^{-\frac{t}{\tau_2}} \quad (1)$$

where $V(t)$is voltage, V_p is peak voltage and t is time. In addition, A,τ_1,$\tau_2$are compensation factor, wave front factor and wavelength factor respectively and the corresponding value of A,τ_1,$\tau_2$are 1.037, 0.4047μs and 68.22μs. 1.2/50μs surge wave simulated by Matlab is shown on Figure 1.

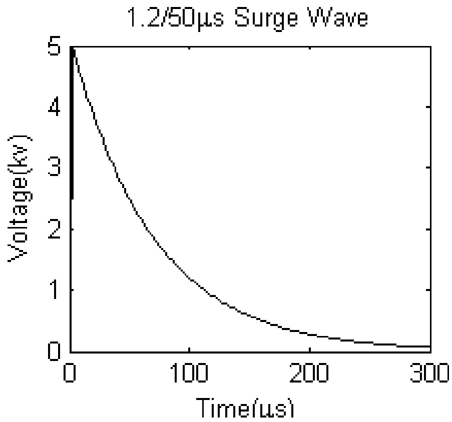


Fig. 1 1.2/50μs surge wave

B. Analysis of surge wave frequency spectrum

The distribution of surge energy at different frequency band can be obtained by Fourier analysis of surge wave. The concentrated area of surge energy is easily found and the specific SPD, which has best protective capability, is given according to the concentrated area. The following equation is Fourier transform of 1.2/50μs surge wave's time-domain expression.

$$V(\omega) = \int_0^{+\infty} V(t)e^{-j\omega t}dt = AV_p(\frac{1}{\frac{1}{\tau_2} + j\omega} - \frac{1}{\frac{1}{\tau_1} + \frac{1}{\tau_2} + j\omega})$$

Therefore, the spectrum function of 1.2/50μs surge wave is given as equation(2), where α is equal to τ_2^{-1}, and β is equal to τ_1^{-1}+τ_2^{-1}.

$$V(\omega) = AV_p(\frac{1}{\alpha + j\omega} - \frac{1}{\beta + j\omega}) \tag{2}$$

The characteristic-curve of 1.2/50μs surge wave frequency spectrum is simulated by Matlab based on A,τ_1 and τ_2, which is given as Figure 2. It can be seen from Figure 2 that most energy of 1.2/50μs surge wave focuses on low frequency. The range of low frequency in 1.2/50μs surge wave is from 0 to 250 kHz. It can be calculated by the engineering approximate formula$f = \frac{1}{\pi T}$(T is wave front time) according to Li [4].

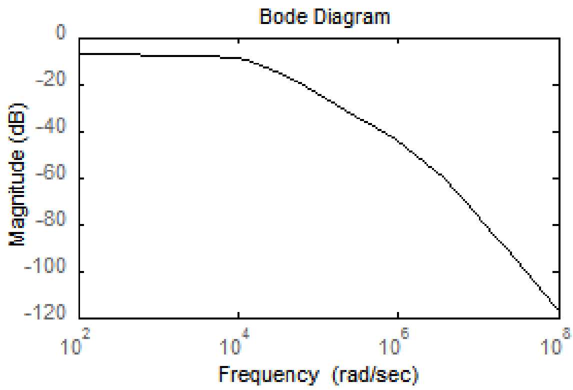


Fig. 2 1.2/50μs Surge wave frequency spectrum

III. Proctection against surge wave

Based on analysis of surge wave, it is known that surge wave is combined with both low and high frequency portion. The low frequency portion contains heavy energy, while high frequency portion has remarkable interference capability. Therefore, surge protection includes two aspects: low-frequency suppression and high- frequency suppression. MOV and TVS are critical for the case of low frequency surge wave suppression because they have the function of voltage-clamp and heavy current bypass. When surge wave pass over MOV or TVS, part of low frequency energy is released and the remaining portion may be under limitation of electronic devices interference level. However, MOV and TVS have limited capability to absorb high frequency surge wave because of distributed inductance and capacitance in SPD. High frequency surge wave has certain amount of energy as mentioned above. Evidence that energy greater than 100mJ will destroy integrated circuit is astonishing [3]. It demonstrates that high frequency surge wave has great impact on sensitive electronic devices. Thus, high frequency surge wave suppression must be taken into consideration. As the study done by Yang indicates the most effective way to absorb high frequency surge wave is to add low pass filter after MOV or TVS in SPD [5]. While high frequency surge wave enter electronic devices via low pass filter, the surge wave voltage potential will decrease rapidly due to the inductance in low pass filter circuit has great damping effect on surge wave and the capacitance has capability to divert lightning current to ground.Therefore, SPD combined with MOV and low pass filter not only absorb the low frequency energy of surge but also decrease the high frequency interference. It can suppress lightning wave effectively.

IV. Selection of surge suppressor and low pass filter

The basic technical specifications of surge suppressor for power supply protection include max clamping voltage, surge current carrying ability and continuous working voltage life [6]. The differences between MOV and TVS among these aspects are shown in Table 1. It is clear that MOV is more suitable to protect against surge wave for AC circuit because of better current carrying ability. Although TVS has superior ability in max clamping voltage and continuous working voltage life, MOV is selected as low frequency surge wave suppressor in SPD in this essay.

TABLE I
DIFFERENCES BETWEEN MOV AND TVS

	MOV	TVS
Max clamping voltage		Better
Surge current carrying ability	Better	
Continuous working voltage life		Better
Price	Cheaper	

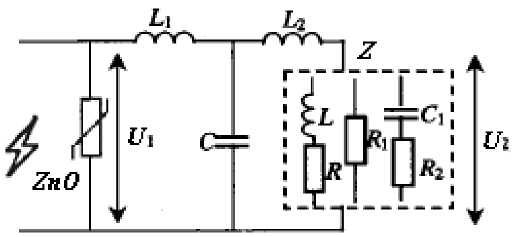


Fig. 3 Combination of MOV and low pass filter

Low pass filter is classified as C type, L type, LC type and T type. SPD combined with MOV and different low pass filter has significant difference in surge protective capability. The study done by Yang gives sufficient evidences to illustrate it. If SPD is combined with MOV and C type low pass filter, the response time of MOV will drop down [5]. Also, the study indicates SPD combined with MOV and L type low pass filter has lower voltage limitation ability, which can be improved by making larger inductance coil [5]. Therefore, C type or L type low pass filter are not ideal surge wave suppressor while T type is exactly one. An illustration of SPD combined with MOV and L type low pass filter is provided in Figure 3. The equation (3) is the transfer function for T type low pass filter related to load impendence according to Figure 3.

$$G(s) = \frac{U_2(s)}{U_1(s)} = \frac{Z}{CL_1L_2s^3 + CL_1Zs^2 + (L_1 + L_2)s + Z} \tag{3}$$

The equation (4),(5) and (6) are corresponding transfer functions while load is resistor, RL and RC respectively.

$$G(s) = \frac{R_1}{CL_1L_2s^3 + CL_1R_1s^2 + (L_1 + L_2)s + R_1} \tag{4}$$

$$G(s) = \frac{Ls+}{(CL_1L_2 + CL_1L)s^3+} \rightarrow$$

$$\rightarrow \frac{R}{CL_1Rs^2 + (L + L_1 + L_2)s + R} \quad (5)$$

$$G(s) = \frac{R_2sC_1+}{CC_1L_1L_2s^4 + CC_1L_1R_2s^3+} \rightarrow$$

$$\rightarrow \frac{1}{(CL_1 + C_1L_1 + C_1L_2)s^2 + R_2C_1s + 1} \quad (6)$$

V. Impedance characteristics of protective objects

Practically, there are three types of power supplies used for automation devices in power distribution system: AC/DC with huge filtering capacitance, DC/DC power supply with huge filtering capacitance and AC/AC power supply without DC filtering capacitance. Both AC/DC and DC/DC power supplies have two different circuits design, one is traditional and the other is recent developed. The former does not have PFC module, while the latter always haven PFC module. The traditional power supply has low power factor, the load connected to it can be treated as RC load. While the recent developed power supply has high power factor which is nearly equivalent to 1, the load connected to it can be simulated as resistor. In addition, the load connected to AC/AC power supply can be seen as RL load because inductance in transformer has primary effect on determining load attributes.

VI. Analysis of surge suppressor effectiveness

To analyze the effectiveness of surge suppressor, Matlab is used for simulating the power supply system with different impendence mentioned above. Before simulating, the key parameters related to surge wave or SPD should be identified. Surge wave applied to the circuit given by Figure 3 is 5kV, 1.2/50μs surge wave. The limit voltage of surge wave after MOV (the specification is 470V) is found at 700V approximately by using piecewise linearization method to simulate circuit response. Additionally, the middle value of inductance and capacitance in T type low pass filter which is matching 470V MOV are given as 20mH and 4μF according to research done by Yang[5]. The reasons they given include two aspects: one is the larger of inductance and capacitance in T type low pass filter are, the better effectiveness will be achieved to limit voltage; the other is negative overvoltage will be caused by larger inductance and capacitance as well as it may result in longer oscillation time. In the following simulation, parameters setting of SPD are as above mentioned. In addition, the principle of selecting power supply used for automation devices in power distribution system is put DC power supply into prior consideration [7]. Based on the above analysis related to impedance characteristics of power supply, only resistance load and RC load are subjected to analyze in this essay.

A. Analysis of circuit response in resistance load

Output voltage (U_2) waveform by T type low pass filter under various resistance loads is illustrated in Figure 4. Comparing to four waveforms in Figure 4, it can be seen clearly that the larger load impendence will bring about the following unfavorable results: higher peak value of U_2, longer and more strenuous vibration. In order to obtain better protection, the impendence of resistance load should be taken in low value. If the load connected power supply is very large, increasing the value of inductance and capacitance in T type filter is the best method to get superior output voltage waveform. However, the value is suggested not to be too large because negative overvoltage will be caused by larger inductance and capacitance as well as it may result in longer oscillation time.

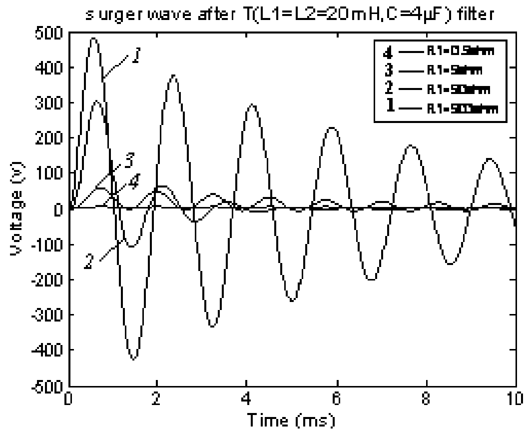
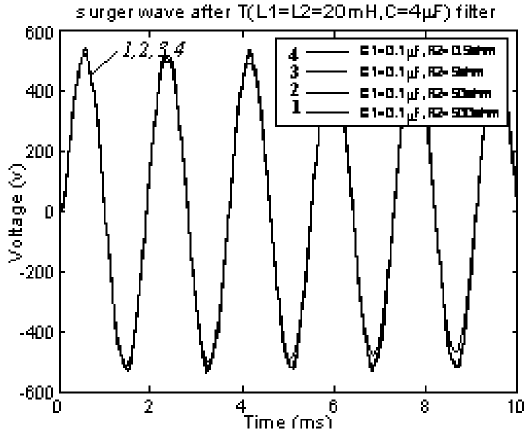


Fig. 4 Output voltage waveform by T type low pass filter under various resistance loads(R_1 equals to 900Ω, 90Ω, 9Ω and 0.9Ω respectively in wave 1, 2, 3 and 4)

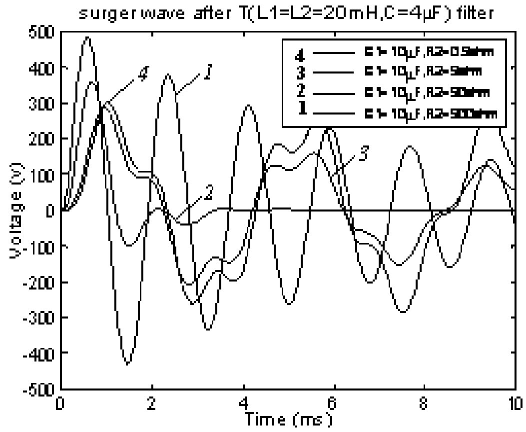
The simulating result indicates that SPD combined with MOV (the specification is 470V) and T type low pass filter (L_1=L_2=20mH, C=4μF) is suitable for resistance load whose impendence value is less than 900Ω to against surge wave. In addition, the impendence value of automation devices in power distribution system is determined by its power consumption. Therefore, automation devices in power distribution system with recent developed power supply, which have less than 900Ω resistance and more than 500W power consumption, are suggested to use the exact SPD to absorb surge wave energy.

B. Analysis of circuit response in RC load

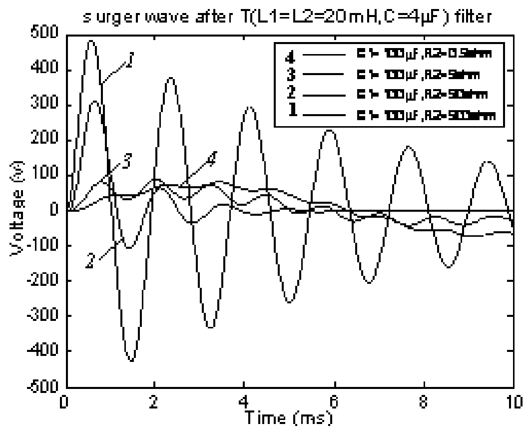
Output voltage (U_2) waveform by T type low pass filter under various RC loads is illustrated in Figure 5. When the value of capacitance in RC load is less than 0.1μF, the waveform of voltage output keep vibrating. Furthermore, amplitude and oscillation time of voltage output waveform are not relevant to the value of resistance in RC load. When the value of capacitance in RC load is among 0.1μF and 100μF, distorted waves is shown in the circuit response waveform of T type filter. When the value of capacitance in RC load is more than 100μF, resistance in RC load has significant impact to the voltage output waveform of T type filter. The waveform of circuit response is similar to that of resistance load. These findings demonstrate that convergence velocity of output vibrated waveform decrease remarkably when reducing the value of capacitance on the basis of maintained resistance in RC load.



(a)

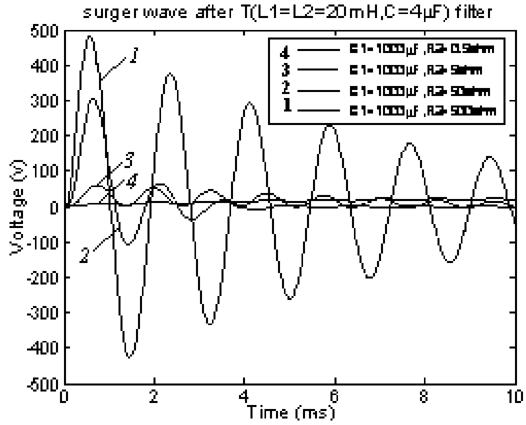


(b)



(c)

The simulating result indicates that T type filter has a perfect match with RC load if it has a high impendence value. In detail, the output waveform not only can stabilize rapidly but also has a low peak value. SPD combined with MOV and T type low pass filter(L_1=L_2=20mH, C=4μF)is suitable for RC load whose resistance value is less than 900Ω and capacitance value is more than 100μF to against surge wave.



(d)

Fig. 5 Output voltage waveform by T type low pass filter under various RC loads (C_1has corresponding value in terms of(a) (b) (c) (d) Figures: 0.1μF, 10μF, 100μF and 1000μF. R_2 equals to 900Ω, 90Ω, 9Ω and 0.9Ω respectively according to wave 1, 2, 3 and 4 in each figure.)

Therefore, automation devices in power distribution system with traditional power supply who have low resistance and large capacitance are recommended to use the exact SPD to absorb surge wave energy.

VII. Conclusion

Interference of power supply used for automation devices in power distribution system caused by lightening surge has been proven as one of the major reasons result in power distribution system accident. Surge wave consists of low frequency portion with high energy and high frequency portion with remarkable interference capability. It is an effective way by setting SPD combined with MOV and T type low pass filter before power supply input to release surge wave energy. For the reason that different power supply systems have different load impendence, the effectiveness of surge suppression may result various. Simulation shows: 1) In order to obtain fast convergence property of surge wave residual voltage, low pass filter should have a perfect match with load impendence. Otherwise, longer and more strenuous vibration will be caused. 2) SPD mentioned above is suitable for resistance load with low impendence or RC load with low resistance and large capacitance to release the surge energy. Therefore, automation devices in power distribution system with traditional power supply who have less than 900Ω resistance and more than 100μF capacitance value or with recent developed power supply who have less than 900Ω resistance and more than 500W power consumption are suggested to use the exact SPD to absorb surge wave energy.

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