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A Study on the Reliability of DVR in a 3-Phase Phase-Controlled Rectifier

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Abstract

This study investigated the relationship between the response time of DVR (Dynamic Voltage Restorer) and the possible compensation range for voltage dips by the DVR system which protects the 3-phase phase-controlled rectifier from said dips. As a result, the permissible range of voltage dip is presented in a 3-phase phase-controlled rectifier. When the DVR compensates for voltage dip, the range of voltage dip can be compensated according to the DVR's response time. Using the proposed method, DVR response time can be determined from the parameters of the 3-phase phase-controlled rectifier and the possible compensatory range of voltage dip, while at the same time it is possible to use a control system having an appropriate speed. Therefore, the use of excessively fast equipment can be avoided, improving the stability of the overall system. The reliability of the DVR concerning the 3-phase phase-controlled rectifier can be verified by simulation.

Key Words : DVR, Response Speed, Voltage Dip, 3-Phase Phase-Controlled Rectifier

1. Introduction

A voltage dip is a phenomenon by which a voltage reduction greater than 20% occurs momentarily for 0.05~0.1 seconds. This phenomenon is typically caused by accidents such as short-circuiting and surges. A voltage dip primarily causes malfunctions in control units; it also causes commutation failure on switching elements for large factories that use inverters, resulting in overall system failure[1]. The problems caused by voltage dips are particularly severe in locations that consist of SCR converters and inverters[2]. Recently, a DVR (Dynamic Voltage Restorer) has been utilized as a solution for voltage dips that cause severe damage to rolling processes in iron mills and in semi-conductor factories. Unlike a UPS(Uninterrupted Power Supply) that compensates for total load capacity, the DVR only compensates for the reduced voltage, making it an alternative countermeasure for voltage dips at large load capacities where a UPS cannot be installed. Thus, the DVR has become the center of focus as

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a solution for voltage dips which fall under most categories of power failure.

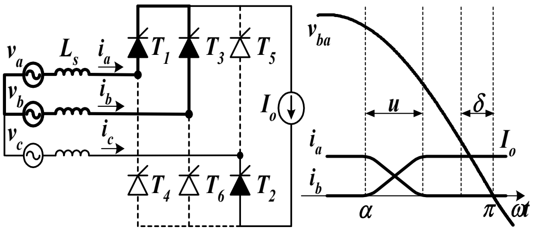
A great deal of research has focused on the DVR[3-7]. Despite this quantity of research, no research had yet tried to determine the range of voltage dip that can be compensated for by the DVR at a specific system. ITIC[8] used a CBEMA curve to suggest the possible range and occurrence time of voltage dips for various electrical devices, while Bollen[9] researched the allowable range, phase and duration of voltage dips when using DVR. However, this only suggested an estimated range for voltage dips for ordinary electrical devices and systems.

This study aims to research the relationship between the possible compensation range of voltage dip, and the response time of DVR, which is an important factor to consider when designing the DVR to protect systems composed of 3-phase phase-controlled. This paper also looks at the magnitude and phase range of voltage dips that can be compensated for according to the DVR response time.

If the suggested method is utilized with control conditions of a 3-phase phase-controlled rectifier and ranges of voltage dips to be compensated for, the response time can be determined, which will help define the response speed of a DVR controller for safest operation. The reliability of the DVR for 3-phase phase-controlled rectifier can also be verified.

2. 3-phase phase-controlled rectifier

Fig. 1 presents the current overlapping phenomenon caused by the inductance of power line, and its corresponding state of SCR, voltage and current waveform of a 3-phase phase-controlled rectifier. Here, α represents the firing angle, u represents overlapping interval, and δ represents SCR's turn-off time.



(a) operation state (b) voltage and current waveform

Fig. 1. The commutation

If commutation failure is observed at T_1 and is not completely turned off, T_1, T_2, T_3 are maintained in the ON state. When the next trigger sign is sent to T_4 allowing T_4 to be turned ON, a short circuit is produced between T_1 and T_4, which destroys the phase-controlled rectifier, possibly causing severe damage to the entire system.

3. Commutation failure caused by voltage dips

Since a single phase voltage dip observed at the A phase or B phase may effect the commutation failure of SCR T_1, the single phase voltage dip on A phase and B phase respectively was investigated.

3.1 Single phase voltage dip on A phase

If a voltage dip occurs on the A phase, the reverse voltage applied at T_1 is as shown in (1).

$$v_{ba,Adip} = \sqrt{2}V_m cos\left(\omega t - \frac{\pi}{3}\right) - \sqrt{2}V_{dip} cos\left(\omega t + \frac{\pi}{3} + \phi\right) = \sqrt{A^2 + B^2} sin(\omega t + \gamma_A) \tag{1}$$

where, $$A = \sqrt{2}\left[V_m \frac{\sqrt{3}}{2} + V_{dip} \sin\left(\frac{\pi}{3} + \phi\right)\right]$$

$$B = \sqrt{2}\left[\frac{V_m}{2} - V_{dip} \cos\left(\frac{\pi}{3} + \phi\right)\right]$$

$$\gamma_A = \tan^{-1}\left(\frac{B}{A}\right)$$

In (1), $(\pi - \gamma_A)$ and $(\alpha - \pi/3)$ are the value where the reverse voltage equals 0. Considering the SCR turn-off time(δ), commutation must be completed within $(\pi - \gamma_A - \delta)$ and $(\alpha - \pi/3 - \delta)$, respectively.

If the integral value of reverse voltage is less than $2\omega L_s I_o$, commutation failure occurs.. The point at which commutation fails is represented as,

$$\alpha > \left(\frac{2\pi}{3} - \gamma_A\right) : \int_{\alpha}^{\pi - \gamma_A - \delta} v_{ba,dip}\, d\omega t < 2\omega L_s I_o$$

$$\alpha \le \left(\frac{2\pi}{3} - \gamma_A\right) : \int_{\alpha}^{\alpha + \pi/3 - \delta} v_{ba,dip}\, d\omega t < 2\omega L_s I_o \quad (2)$$

If (1) is applied to equation (2) it can be summarized as follows in (3),

$$\alpha > \left(\frac{2\pi}{3} - \gamma_A\right) : \sqrt{A^2 + B^2}\left[\cos(\alpha + \gamma_A) - \cos(\pi - \delta)\right] < 2\omega L_s I_o$$

$$\alpha \le \left(\frac{2\pi}{3} - \gamma_A\right) : \sqrt{A^2 + B^2}\left[\cos(\alpha + \gamma_A) - \cos\left(\alpha + \frac{\pi}{3} - \delta + \gamma_A\right)\right] < 2\omega L_s I_c \quad (3)$$

3.2 Single phase voltage dip on B phase

If a voltage dip occurs on phase B, the reverse voltage applied at T_2 is as shown in (4).

$$v_{ba,Bdip} = \sqrt{2}V_{dip} \cos\left(\omega t - \frac{\pi}{3} + \phi\right) - \sqrt{2}V_m \cos\left(\omega t + \frac{\pi}{3}\right) = \sqrt{C^2 + D^2} \sin(\omega t + \gamma_A) \quad (4)$$

where, $$C = \sqrt{2}\left[V_m \frac{\sqrt{3}}{2} + V_{dip} \sin\left(\frac{\pi}{3} - \phi\right)\right]$$

$$D = \sqrt{2}\left[V_{dip} \cos\left(\frac{\pi}{3} - \phi\right) - \frac{V_m}{2}\right]$$

$$\gamma_B = \tan^{-1}\left(\frac{D}{C}\right)$$

By applying a method similar to the A phase, the conditions that will cause commutation failure can be summarized as (5).

$$\alpha > \left(\frac{2\pi}{3} - \gamma_B\right) : \sqrt{C^2 + D^2}\left[\cos(\alpha + \gamma_B) - \cos(\pi - \delta)\right] < 2\omega L_s I_c$$

$$\alpha \le \left(\frac{2\pi}{3} - \gamma_B\right) : \sqrt{C^2 + D^2}\left[\cos(\alpha + \gamma_B) - \cos\left(\alpha + \frac{\pi}{3} - \delta + \gamma_B\right)\right] < 2\omega L_s I_o \quad (5)$$

3.3 Permissible range of voltage dip

Possible occurrences of commutation failure by a voltage dip under specific load conditions were observed using (3), (5). Table 1 shows the parameters of a phase-controlled rectifier and Fig. 2 shows the relationship between the voltage dip and commutation failure following the conditions of Table 1.

Table 1. The parameters of phase-controlled rectifier

AC input power		460V	Frequency	60Hz
Rectifier rating	Voltage	300V	Overload ratio	150%
	Current	360A	Power source Inductance	60㎌H

Fig. 2 is a graph showing the possible occurrence of commutation failure depending on phase shifts, and the intensity of input voltage at firing angles of 70°, 100°, 130°, and 160°. The horizontal axis is the voltage dip rate where the amount of voltage reduction by voltage dip is compared to the normal voltage then converted into percentile value, while the vertical axis is the phase shift of the input voltage. The graph shows each area where commutation failure is observed as a result of a 3 phase parallel voltage dip and single phase voltage dip. A normal state of input voltage would show 0% voltage dip, and 0° phase shift; the right side of the graph is the region which causes commutation failure. From Fig. 2, the range of voltage dips for various firing angles of phase-controlled rectifier that does not cause commutation failure can be observed. We can also observe that as the firing angle and phase shift of the input voltage increases, even minor changes in input power can cause commutation failure. Single phase voltage dips do not cause commutation failure when the firing angle is less than 130°, while it does cause commutation failure at a 3-phase parallel voltage dip.

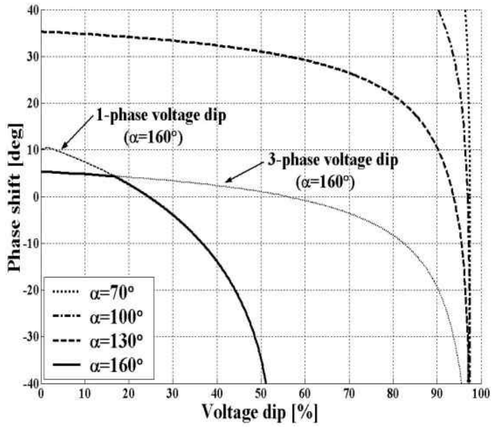


Fig. 2. The permissible range of voltage dip according to firing angle

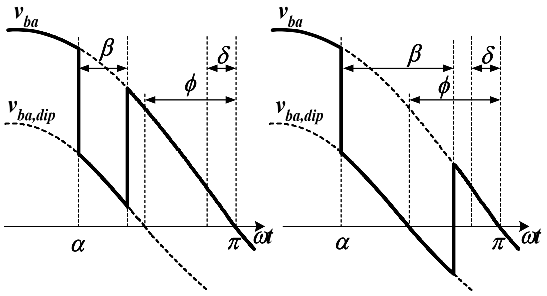
Statistically, a voltage dip with a voltage reduction ratio of less than 60% accounts for approximately 90% of voltage dips [2,10,11]. It may be assumed that if the maximum firing angle for facility described on Table 1 is limited to 149°, in voltage dips that are less than 60% of the voltage reduction, commutation failure would not occur. with a limited maximum value for the firing angle, restoration of compensatory energy produced at the loading side to the line voltage would decrease. Therefore, additional systems, such as a dynamic breaker or chopper, that spend additional compensation energy as resistance are needed in order to prevent voltage increases in the DC link caused by compensation energy.

4. Relationship between commutation failure and DVR response time

This section looks at the relationship between DVR response time and the range of compensation voltage dip. In order to investigate the conditions in which the shortest amount of time was taken for commutation failure to occur once a voltage dip was produced, only those sections with a firing angle over 120° are considered for both 3-phase parallel voltage dips and single phase voltage dips. Methods to compensate for the voltage dip include minimizing the size of compensation voltage, minimizing the size of compensation energy, and restoring load voltage to its state prior to the voltage dip as the ways[12]. This study will consider only the method of restoring the state of the 3-phase phase-controlled rectifier to its state prior to the voltage dip. As previously explained in the analysis of results, minimizing the size of compensation voltage and compensation energy cannot be used on a 3-phase phase-controlled rectifier because this rectifier is affected by the phase of voltage, and this method will produce different phases of voltage before and after the occurrence of the accident.

Fig. 3 shows reverse voltage v_{ba} at SCR T_1 with a firing angle greater than 120°. v_{ba} is beginning normal voltage , a voltage dip is produced at point

α when a trigger signal is sent to T_3, and compensation voltage is sent by a DVR after β amount of time has passed to restore the v_{ba} to its normal voltage value. Specific classification is given to the point where the DVR sends compensatory energy as it is greater than or less than the point $(\pi - \phi)$ where the reverse voltage $v_{ba,dip}$ changes its sign.



(a) $(\alpha + \beta) \leq (\pi - \phi)$ (b) $(\alpha + \beta) > (\pi - \phi)$

Fig. 3. Voltage dip and compensation voltage

As shown in Fig. 3(a), the condition that causes commutation failure where $(\alpha + \beta)$ is less than $(\pi - \phi)$ can be expressed as,

$$\int_{\alpha}^{\alpha+\beta} v_{ba,dip}\, d\omega t + \int_{\alpha+\beta}^{\pi-\delta} v_{ba}\, d\omega t < 2\omega L_s I_c \tag{6}$$

The situation 3(b) where $(\alpha + \beta)$ is greater than $(\pi - \phi)$ not only causes commutation failure in condition (6), but also in condition (7).

$$\int_{\alpha}^{\pi-\phi} v_{ba,dip}\, d\omega t < \int_{\pi-\phi}^{\alpha+\beta} v_{ba}\, d\omega t \tag{7}$$

This is to say, if the left side of (7) is greater than the right side of the equation, T_3 is completely turned OFF before $(\alpha + \beta)$. Even if the DVR sends compensatory energy after $(\alpha + \beta)$, it will not be enough to turn the T_3back ON, which will result in commutation failure.

Fig. 4 shows the relationship between ranges of voltage dips that can be protected from commutation failure, to the response time of the DVR tested in the facility as described in Table 1. Here, it was assumed that phase changes did not occur. If DVR response time is more than 0.53ms from Point A of Fig. 4, no compensation effect will occur. If DVR response time is set as 0.29ms from Point B onwards, the 3-phase phase-controlled rectifier with a maximum firing angle of 160° can be compensated for regardless of operation state as long as the voltage reduction rate is less than 60%. Although possible compensation areas can be enlarged with shorter DVR response time, it has the minor effect causing a rapid price increase for a DVR controller composed of a system using microprocessors. However, the method presented in this paper allows a user to design the DVR controller with optimum response time, which will reduce costs by not using excessively rapid devices for the DVR controller, and can also improve the stability of the DVR control program.

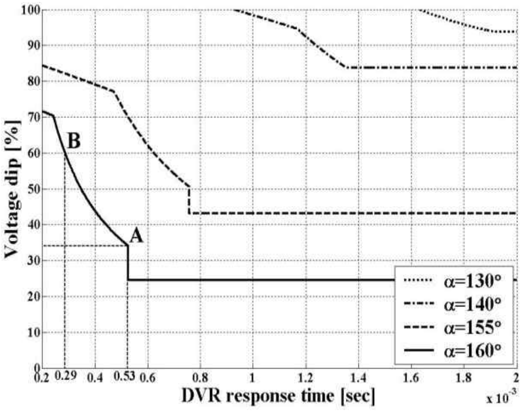


Fig. 4. The range of voltage dip which that can be compensated for according to the response time of DVR and firing angle when the phase is not unchanged

5. Simulation results

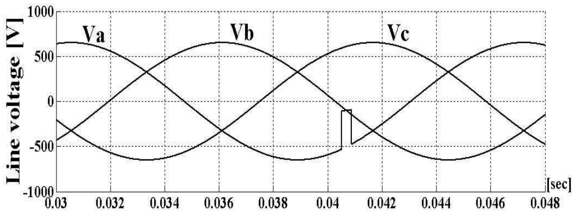
In order to verify the proposed method, a simulation was conducted using a MATLAB Power System Blockset.

Figs. 5 and 6 show the waveform of the rectifier when line voltage is compensated by DVR. The condition of simulation is as follows: with a firing angle of 155°, a single phase voltage dip has an 80% voltage reduction rate, and the parameters of Table 1 are used. Also it was assumed that once voltage dip occurs, the DVR restores the voltage and the line input voltage phase to its original state prior to the dip. From Fig. 4, which shows the range of voltage dips that can be compensated for according to the response time of the DVR, it can observed that 366μs is the maximum response time of a DVR that can protect the rectifier when the firing angle is 155° and voltage reduction rate is 80%.

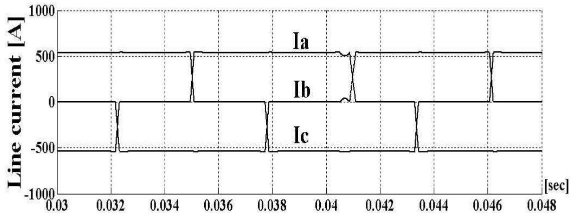
Fig. 5 shows the waveform of a phase-controlled rectifier when DVR response time is set at 366μs. Fig. 5(a) represents the waveform of line voltage compensated for by a DVR, which shows the reduction of the line voltage at phase A by the voltage dip, and its restoration by the DVR after 366 μs. Fig. 5(b) shows the phase current of the rectifier. It was set to cause a voltage dip as soon as the trigger signal was sent to SCR T_3, thus commutation is not conducted between phase A and phase B when the voltage dip occurs. Instead, commutation takes place successfully as soon as the line voltage is compensated for after the DVR response time. The output waveform of a phase-controlled rectifier is presented in Fig. 5(c), which shows that the DVR effectively restores the voltage dip for the normal operation of the rectifier.

Fig. 6 presents the waveform when the response time of the DVR was set to 367μs. The occurrence of a voltage dip at line voltage and the restoration to the normal state by the DVR after 367μs can be observed in Fig. 6(a), whereas Fig. 6(b) shows the occurrence of commutation failure. When the next trigger signal is sent in Fig. 6(c), output voltage indicates 0, which represents the occurrence of short-circuiting.

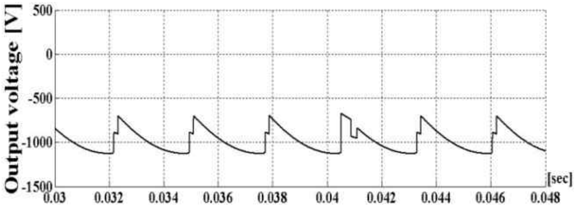
It can therefore be observed that setting the DVR response time below 366μs can protect the facility described in Table 1 from all voltage dips with a voltage reduction rate of up to 80%. The proposed method can be used to obtain the relationship between DVR response time and the permissible



(a) compensated line voltage



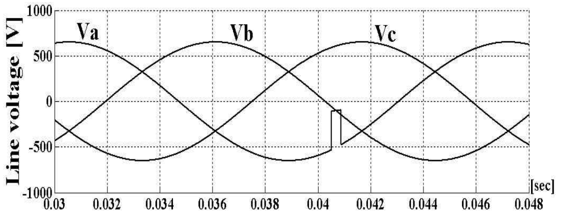
(b) phase current



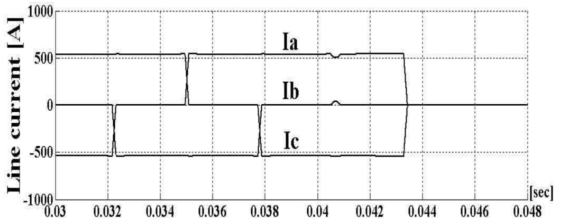
(c) output voltage

Fig. 5. Waveform when the response time of DVR is 366μs

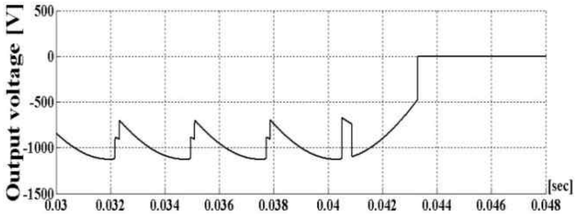
range of voltage dip that can be compensated for, which enables the design of an optimum 3-phase phase-controlled rectifier.



(a) compensated input voltage



(b) phase current



(c) output voltage

Fig. 6. Waveform when the response time of DVR is $367\mu s$

6. Conclusion

This paper suggested a solution for setting the optimum response time of a DVR, which is an important factor to consider when designing a DVR suitable for protecting a 3-phase phase-controlled rectifier from voltage dips. Even an identical intensity of voltage dips may produce different commutation failure results depending on the state of the 3-phase phase-controlled rectifier. Thus, in order to ensure validity, the worst conditions that can cause commutation failure were investigated, and the range of voltage dips that may be compensated for by the DVR per response time was derived. Although reducing the response time of the DVR ensures a wider range of voltage dip that can be compensated for, the cost of the DVR controller rises rapidly and the stability of controller is reduced. However, the method suggested here may be used to calculate the optimum DVR response time required for certain intensities of voltage dips that can protect the characteristics of the 3-phase phase-controlled rectifier. The results of this study can be applied to designing the optimum DVR setting for a 3-phase phase-controlled rectifier under specific conditions. A simulation was conducted to verify the reliability of the proposed method.

References

[1] A. Arora, K. Chan, T. Jauch, A. Kara, and E. Wirth, “Innovative system solutions for power quality enhancement,” ABB review, pp. 4-12, March 1998.

[2] BENACHAIBA Chellali, FERDI Brahim, Voltage Quality Improvement Using DVR, Electrical Power Quality and Utilisation, Journal Vol. XIV, No. 1, 2008.

[3] S. S. Choi, B. H. Li, and D. M. Vilathgamuwa, “Dynamic voltage restoration with minimum energy injection,” IEEE Transactions on Power Systems, vol. 15, no. 1, pp. 51-57, February 2000.

[4] C. Zhan, C. Fitzer, V. K. Ramachandaramurthy, A. Arulampalam, M. Barnes, and N. Jenkins, “Software phase-locked loop applied to dynamic voltage restorer (DVR),” Power Engineering Society Winter Meeting 2001 IEEE, vol. 3, pp. 1033-1038, February 2001.

[5] S. S. Choi, B. H. Li, and D. M. Vilathgamuwa, “Design and analysis of the inverter-side filter used in the dynamic voltage restorer,” IEEE Transactions on Power Delivery, vol. 17, no. 3, pp. 857-864, July 2002.

[6] C. Fitzer, M. Barnes, and P. Green, “Voltage sag detection technique for a dynamic voltage restorer,” IAS Annual Meeting, vol. 2, pp. 917-924, Oct. 2002.

[7] Bingsen Wang, Giri Venkataramanan and Mahesh Illindala, “Operation and Control of a Dynamic Voltage Restorer Using Transformer Coupled H-Bridge Converters”, IEEE transactions on power electronics, VOL. 21, NO. 4, JULY 2006.

[8] J. Arrillaga, N. R. Waston, and S. Chen, Power System Quality Assessment, John Wiley & Sons, 2000.

〔9〕 M. H. J. Bollen, “Voltage, power and current ratings of series voltage controllers,” Power Engineering Society Winter Meeting 2000 IEEE, vol. 4, pp. 2910-2915, January 2000.
〔10〕 Norbert EDOMAH, “Effects of voltage sags, swell and other disturbances on electrical equipment and their economic implications”, Paper 0018, 20th International Conference on Electricity Distribution, Prague, 8-11 June 2009.
〔11〕 D. M. Vilathgamuwa, A.A.D.R. Perera, S.S. Choi, Voltage sag compensation with energy optimized dynamic voltage restorer, IEEE Trans. Power Deliver.18(3), 928-936, 2003.
〔12〕 S. Polmai, T. Ise, and S. Kumagai, “Experiment on voltage sag compensation with minimum energy injection by use of a micro-SMES,” IEEE PCC-Osaka 2002, vol. 2, pp. 415-420, April 2002.

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