Mitigation Voltage Sag Using DVR with Power Distribution Networks for Enhancing the Power System Quality

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Abstract – *The fast developments in power electronics technology have made it possible to mitigate voltage disturbances in power system. Among the voltage disturbances challenges in the industry, voltage sags are considered the most critical problem to sensitive loads. The Dynamic Voltage Restorer (DVR) is mainly used in a utility grid to protect the sensitive loads from power quality problems, such as voltage sags and swells. Even though the effectiveness of the DVR can wane under unbalanced grid voltage conditions, it is recognized to be the best effective solution to overcome this problem. The primary advantage of the DVR is keeping the users always on-line with high quality constant voltage maintaining the continuity of production. In this paper, the usefulness of including DVR in distribution system for the purpose of voltage sag and swell mitigation is described. This paper also describes the DVR operation strategies and control. The DVR operation with the distribution networks is found very efficient for detecting and clearing any power quality disturbances in distribution system. Results of simulation using MATLAB/Simulink are demonstrated to prove the usefulness of this DVR design and operation to enhance the power system quality.*

Keywords: *Power System Quality, Voltage Sag, DVR and High Voltage.*

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I. Introduction

With the increasing demand for electricity supply, the electrical grid is extended and classified to generation, transmission and distribution. This extension is required to increase the transmission voltage that has now reached up to 1200Kv. To save the system in service, it must be operated with advanced control devices for system stability, high efficiency and reliability. The advanced control techniques can have direct effect for the electrical system to reach the optimize voltage control [1]-[3].

Integration and exploitation of Distributed Generation (DG) systems, such as uncontrollable renewable sources, which can maximize green energy penetration in the utility network, increases the concern of voltage and frequency stability. In addition, voltage distortions and fluctuations are also frequently encountered in weak utility network systems. Ripple currents due to the power electronics converters also cause voltage harmonics and, as a result, the utility voltage waveforms may become distorted. On the other hand, voltage sag and swell problems are usually caused by short-circuit current which causes fault to occur. Voltage sags and swells are defined as a fast reduction or rise of utility voltages which can vary from 10 to 90% during sags and 110 to 180% during swells of its nominal value [1]. The presence of voltage harmonics in the power system is a major power quality problem and needs special attention in reducing its effect. In order to solve these voltage-related power quality problems, industrial and domestic users mostly use autotransformer-based voltage stabilizer [2].

However, mechanically controlled voltage stabilizers can only combat long duration of voltage drops without reducing voltage harmonics. They respond sluggishly to voltage fluctuations and have a response time that is typically greater than 750 ms. Therefore, this low-cost device would not be a viable solution for the case when there are fast voltage variations. The undesirable voltage fluctuations typically last around 10 ms to 1 min. Therefore, custom power devices (CPDs) play an important role in compensating for most power quality problems related to DG integrated utility network systems [3],[4].

One common practice is to characterize the sag magnitude through the remaining voltage during the sag, called ‘retained voltage’. The magnitude of voltage sag can be determined in number of ways like one cycle or half cycle rms voltage, magnitude of fundamental component of voltage sag and peak voltage over each cycle or half cycle. Sag magnitude (retained voltage) is shown in Fig. 1.

The Dynamic Voltage Restorer (DVR) is used to deal with the voltage sag and to reduce the effects of these disturbances on the sensitive loads such as digital computers, Programmable Logic Controllers (PLC), consumer electronics and variable frequency motor drives [5]. Its function is to detect the voltage sag and to inject voltage difference between the pre-sag and post-sag voltage, so the voltage is maintained and reaches the load side as pre-sag voltage magnitude, however the phase angle is not considered crucial to be returned back to the pre-sag condition. This is done by injecting the active and reactive power.

Fig. 2 describes the power circuit of the DVR; it is small in size and best economical solution if compared to other methods. Moreover, choosing proper detection technique in the DVR, the response to the voltage injection could be faster. Unlike un-interruptible power supplies (UPS), DVR supplies only part of the waveform that has been reduced due to voltage sag and not the whole waveform. In addition, the UPS needs high battery maintenance and replacement due to leak, which in order lead to high cost, but the DVR could use small batteries or even no batteries at all depending on the compensation methods used [6]. The current of the DVR is the same as the supply current, where the secondary current is the same as the primary side, due to the turns of ratio of the transformer is 1:1.

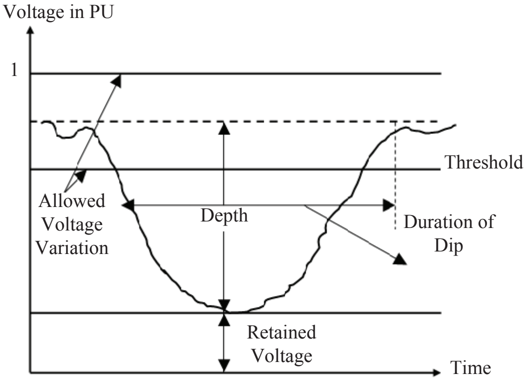

Fig. 1 Sag magnitude (retained voltage)

II. Basic DVR Components

Fig. 2 shows the power and control circuit, which are the two main parts of the DVR. There are various critical parameters of control signals such as magnitude, phase shift, frequency etc. which are injected by DVR. These parameters are derived by the control circuit. This injected voltage is generated by the switches in the power circuit based on the control signals. Furthermore, the basic structure of DVR is described by the power circuit and is discussed in this section. The 5 main important parts of power circuit, their function and requirements are discussed ahead. The power circuit of the studied DVR is a three-phase Hybrid Pulse-Width Modulated (PWM) converter having a DC battery group. The battery group can be recharged using an external battery charger. In the studied system the associated control system does not required to regulate the DC link voltage. The ac side of the Voltage Source Inverter (VSI) is connected to the Point of Common Coupling (PCC) through an inductor and three single-phase transformers. The primary side of the transformers is connected in series between the utility and the load. The secondary side of the transformers is connected in a delta or star configuration to the VSI. This type of connection is very useful during the compensation of unbalanced utility voltages [5]-[7]. Since the system is used for compensation of unbalances, the use of a grounded star point prevents zero-sequence voltages.

Energy storage to be used could be batteries or capacitor bank to provide the real power required during the restoration process of the DVR.

Voltage source inverter will be used to convert the DC supply from the batteries or capacitor banks.

Passive filter which is the Low Pass Filter (LPF) type will be used in switching harmonic components from the injected voltage. In another word, it converts PWM waveform into a sinusoidal waveform. The LPF is an LC series circuit placed either at the inverter side or at the high voltage side of the injecting transformer. Placing the LPF at the inverter side will prevent the higher order harmonics from passing through the transformer and therefore reduces the voltage stress on the injection transformer. While placing the LPF at the HV side of the injection transformer will result in the need of a higher rating transformer, the high harmonic will pass through the injecting transformer.

Meanwhile, voltage injection transformer is used to step up the low AC voltage supplied by the VSI to the required level of the injected voltage.

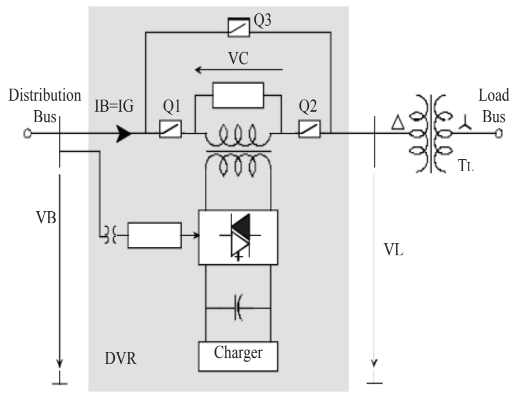

Fig. 2 Principle Design DVR Module

A. Energy Storage Unit

Various devices such as Flywheels, Lead acid batteries, Superconducting Magnetic energy storage (SMES) and Super-Capacitors can be used as energy storage devices. The main function of these energy storage units is to provide the desired real power during voltage sag. The amount of active power generated by the energy storage device is a key factor, as it decides the compensation ability of DVR. Among all others, lead batteries are popular because of their high response during charging and discharging. But the discharge rate is dependent on the chemical reaction rate of the battery. Thus, that the available energy inside the battery is determined by its discharge rate [2]-[5].

B. Voltage Source Inverter

Generally, Pulse-Width Modulated Voltage Source Inverter (PWMVSI) is used. In the previous section, the energy storage device generates DC voltage. To convert this DC voltage into AC voltage a Voltage Source Inverter is used. In order to boost the magnitude of voltage during sag, a step-up voltage injection transformer in DVR power circuit is used. Thus, a VSI with a low voltage rating is sufficient.

C. Passive Filters

Fig. 3 shows the different filter placements. To convert the PWM inverted pulse waveform into a sinusoidal waveform, low pass passive filters are used. In order to achieve this, it is necessary to eliminate the higher order harmonic components during DC to AC conversion in Voltage Source Inverter which will also distort the compensated output voltage. These filters which play a vital role can be placed either on high voltage or low voltage side. Inverter side of the injection transformers can avoid higher order harmonics from passing through the voltage transformer by placing the filters in the inverter side. Hence, it also reduces the stress on the injection transformer. One of the problems which arise when placing the filter in the inverter side is that there might be a phase shift and voltage drop in the inverter output. So, this could be resolved by placing the filter in the load side. But this would allow higher order harmonic currents to penetrate into the secondary side of the transformer, so transformer with higher rating is essential.

D.By-Pass Switch

Now DVR is a series connected device. If there is a fault current due to fault in the downstream, it will flow through the inverter. Now the power components of inverter are not highly rated but normally rated due to its cost. So, in order to protect the inverter, a By-pass switch is used. Generally, a crowbar switch is used which bypasses the inverter circuit. So, crowbar switch will sense the magnitude of the current. If it is normal and within the handling range of inverter components it (the crowbar switch) will be inactive. On the other hand, if current is high it will bypass the components of the inverter.

E. Voltage Injection Transformers

The primary side of the injection transformer is connected in series to the distribution line, while the secondary side is connected to the DVR power circuit. Now 3 single phase transformers or 1 three phase transformer can be used for 3 phase DVR whereas 1 single phase transformer can be used for 1 phase DVR. The type of connection used for 3 phase DVR if 3 single phase transformers are used is called "Delta-Delta" type connection as shown in Fig.4. If a winding is missing on primary and secondary side then such a connection is called "Open-Delta" connection which is as widely used in DVR systems as shown in Fig. 5 [6]-[10].

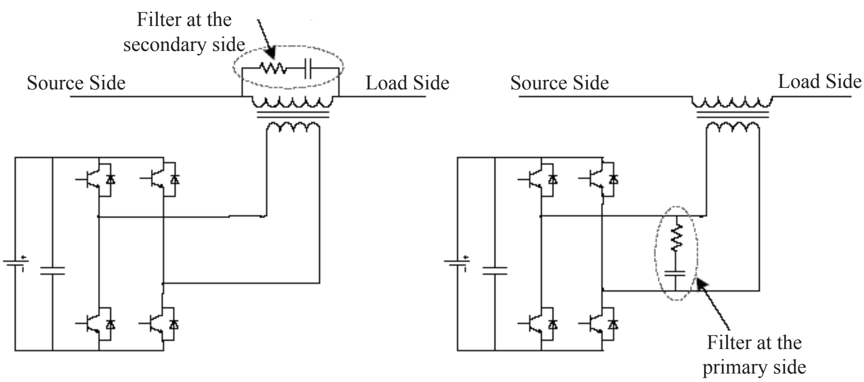

Fig. 3 Different Filter Placements

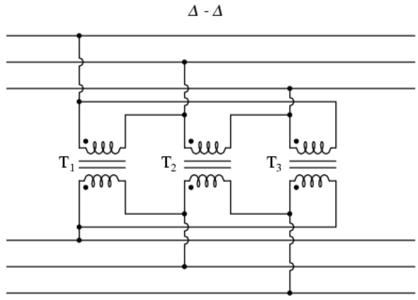

Fig. 4 Connection Method for Injection Transformer Delta-Delta Connection

Basically, the injection transformer is a step-up transformer which increases the voltage supplied by filtered VSI output to a desired level and it also isolates the DVR circuit from the distribution network. Winding ratios are very important and it is predetermined according to the required voltage at the secondary side. High winding ratios would mean high magnitude currents on the primary side which may affect the components of inverter circuit. When deciding the performance of DVR, the rating of the transformer is an important factor. The winding configuration of the injection transformer is very important and it mainly depends on the upstream distribution transformer. In case of a Δ-Y connection with the grounded neutral there will not be any zero-sequence current flowing into the secondary during an unbalance fault or an earth fault in the high voltage side. Thus, only the positive and negative sequence components are compensated by the DVR.

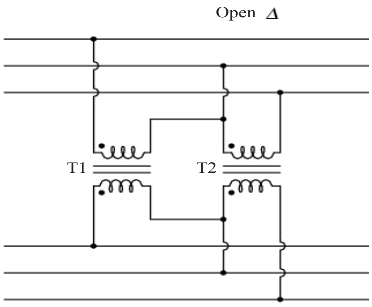

Fig. 5 Connection Method for Injection Transformer Open-Delta Connection

III. Principles of DVR Operation

DVR is a solid-state power electronics switching device which comprises of either Insulated Gate Bipolar Transistor (IGBT) or Gate Turn-Off thyristors (GTO), a capacitor bank as energy storage device and injection transformers. From the Fig. 2, it can be seen that the DVR is connected in between the distribution system and the load. The basic idea of DVR is that by means of an injecting transformer a control voltage is generated by a forced commuted convertor which is in series with the bus voltage. A regulated DC voltage source is provided by a DC capacitor bank which acts as an energy storage device. Fig. 2 shows the principle of the DVR with a Response Time of Less Than One Millisecond. Under normal operating conditions when there is no voltage sag, DVR provides very low magnitude of voltage to compensate for the voltage drop of transformer and device losses. But when there is a voltage sag in distribution system, the DVR will generate required controlled voltage of high magnitude and desired phase angle which ensures that load voltage is uninterrupted and maintained. In this case, the capacitor will be discharged to keep the load supply constant [8]-[12]. Note that the DVR is capable of generating or absorbing reactive power but the reactive power injection of the device must be provided by an external energy source or energy storage system. The response time of DVD is very short and is limited by the power electronics devices and the voltage sag detection time. The expected response time is about 25 milliseconds, which is much less than some of the traditional methods of voltage correction such as tap-changing transformers.

The operation modes of the DVR are classified to three modes as:

A. During voltage sag/swell on the line

The difference between the pre-sag voltage and the sag voltage is injected by the DVR by supplying the real power from the energy storage element and the reactive power. The DVR injects the difference between the pre-sag and the sag voltage, by supplying the real power requirement from the energy storage device together with the reactive power. Due to the ratings of DC energy storage and the voltage injection transformer ratio the maximum capability of DVR is limited. The magnitude of the injected voltage can be controlled individually in case of three single-phase DVRs. With the network voltages, the injected voltages are made to be synchronized (i.e. same frequency and the phase angle) [12]-[14].

B. During the normal operation

During the normal operation as there is no sag, DVR will not supply any voltage to the load. It will be in a standby mode or it operates in the self-charging mode if the energy storage device is fully charged. The energy storage device can be charged either by the power supply itself or from a different source.

C. During a short circuit or fault in the downstream of the distribution line

In this case we have seen before that a bypass switch (crossbar switch) will be activated and it will bypass the inverter circuit in order to protect the electronic components of the inverter.

IV. DVR Control

The inverter Pulse-Width Modulated (PWM) switching may pose an additional time delay element in the DVR systems. The average time delay of inverter PWM switching can be assumed to be a half of the switching period. If the PWM switching frequency is high enough compared to the time delay of the control system, the voltage response by use of an ideal linear amplifier or a PWM inverter may make no difference in DVR systems except for some switching frequency ripples at output voltage [5]. However, the switching frequency cannot be increased infinitely because of the limitation of switching devices. This section discusses the minimum inverter switching frequency, which is critical to guarantee the performance of DVR systems is similar to the case of ideal linear amplifiers.

In this section, a DVR's performance in a sample distribution network is investigated. Fig. 6 and Fig. 7 show the simulation results of the proposed DVR control system with the closed loop damping factor of 0.5 when the switching frequency was set to be 10 kHz and 5 kHz respectively. Fig. 6 shows very stable and good dynamics output compensation voltage since that the switching frequency was set to two times higher than the critical switching frequency. The output compensation voltage is settled around 5Td=500µs which is almost the same with the simulation results of Fig. 6. It adopts an ideal linear amplifier model. The inverter for this simulation equation and control logic are described in [5][6]. Although the ripple and the settling time are slightly increased, the output compensation voltage is stable and has good control dynamics when the switching frequency is equal to the minimum switching frequency in Fig. 7.

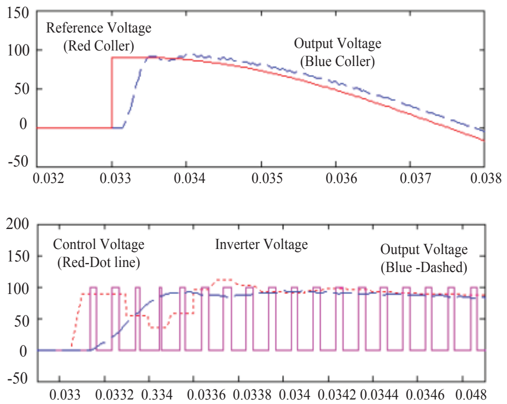

Fig. 6 Voltage response of a digital controlled DVR with time delay

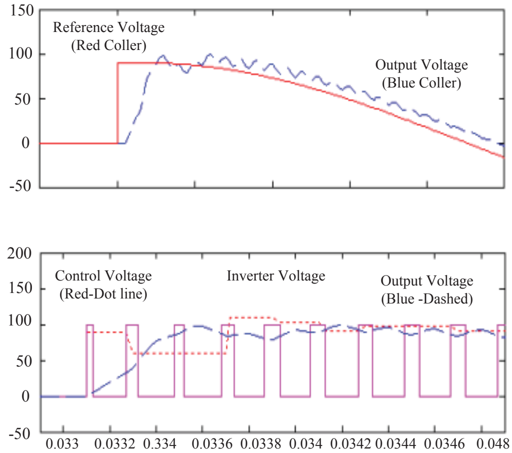

Fig. 7 Voltage response of a digital controlled DVR with time delay

V. Simulation of DVR

Experiments have been performed to verify the proposed control algorithm on a DVR system. Fig. 8 shows the experimental DVR system. The rated line voltage of the grid is 220 Vrms/ 60Hz. 50% symmetrical voltage sags were generated by the power source, SW5250A/ELGAR [6]. The fault was generated over 50 ms. The experimental condition is set as in Table I. The DVR consists of a 6-leg inverter, three LC output filters, and three angle-phase matching transformers. The 6-leg inverter has 12 IGBT switches and a DC power supply in the DC link. The switching frequency of the IGBT switches is 10 kHz.

TABLE I
EXPERIMENTAL CONDITION

T	100 µsec
F	10 kHz
R load	40 Ω
R_f	0.4 Ω
C_f	80 µF
W_f	400 µH
ω_f	2π(890Hz)

A. Experiment Result

Fig. 9 shows the experimental waveforms of the proposed DVR control system. The DVR compensates the voltage sags over 50ms. Since the control of the output compensation voltage is independent in each phase, only the a-phase voltage waveform is shown for convenience. The waveforms of the upper window of Fig. 9 show the reference compensation voltage and the actual output compensation voltage in relatively long-time interval. The waveforms of the lower window of Fig. 9 show the zooming for the reference compensation voltage and the actual output compensation voltage at the instant of the abrupt change of the reference compensation voltage [6],[12]-[14]. No over shoot is observed in the output compensation voltage. The output compensation voltage decently converges to the reference compensation voltage within 500µs. This total time delay comes from the pure control delay, the inverter switching, sensing time, and the LC output filters. Fig. 10 shows the voltage of one of the phases load (A) with and without DVR. Fig. 11 shows the voltage (p.u.) of one of the phases load (A) with and without DVR.

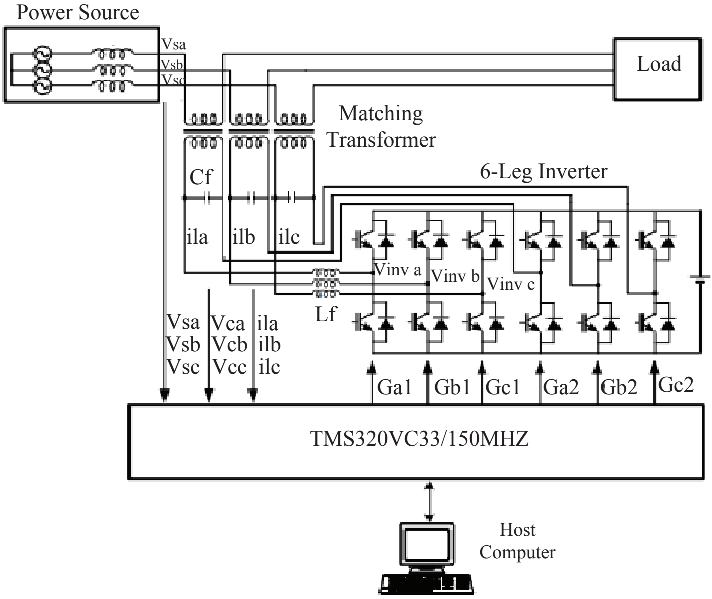

Fig. 8 Experimental DVR system with DSP control board

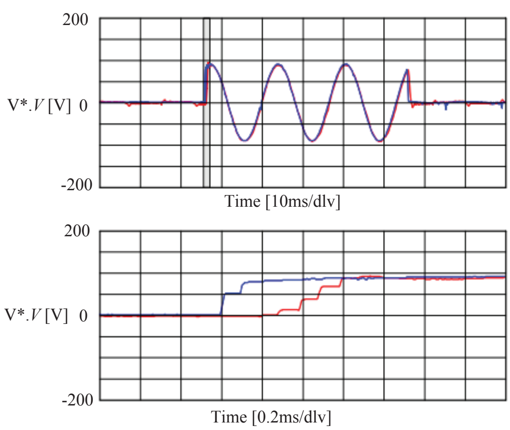

Fig. 9 Experimental voltage response of digital controlled DVR with time delay of Tf /12; fsw=10kHz, ξ=0.5.

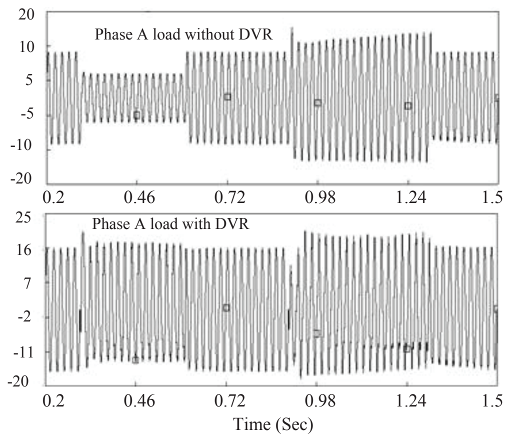

Fig. 10 Voltage of one of the phases' load (A) with and without DVR

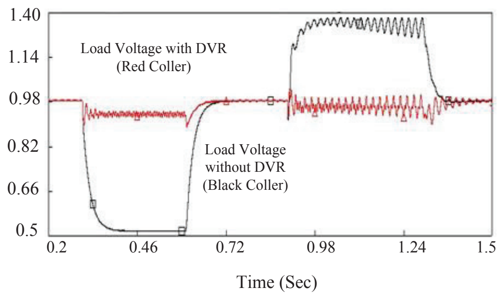

Fig. 11 Voltage (pu) of one of the phases' load (A) with and without DVR

VI. Conclusion

Power system quality is a vital issue for electricity companies and consumers of low and medium voltage. To appropriately meet the consumer requirements, electricity companies have tried to improve power quality. There are different definitions for power quality. For instance, electricity companies define power quality as reliability and they can statistically demonstrate how reliable a network is. In contrast, electrical equipment manufacturers define power quality as guaranteeing performance of devices based on power supply characteristics. The Voltage sags of more than 50% and duration of two cycles were compensated by the proposed DVR connected system supplying an induction motor. The voltage compensation levels were observed accurately and the line voltages were restored during the sag period precisely since the SPWM pulses were generated at a higher frequency of 5 kHz, thus improves the power quality. Power quality problems, such as sag and swell, can have adverse impact on the performance of critical loads. These power quality problems can even cause undesired turning-off of these loads. Among them, voltage unbalance is considered as the major affecting problem leads to degradation in performance of electrical equipment. The simulation result shows that DVR compensate sag/swell effectively and provide good voltage regulation. The performance of DVR is satisfactory. In this paper DVR has been presented to improve the power system quality. Also, in this paper the guidelines have been verified by an experimental DVR system that shows very good performance as expected by the analysis and simulations. Further study is going on to decrease the time delay of the control system of DVRs.

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