OPERATION MODES ANALYSIS FOR A DVR IN DISTRIBUTION GRIDS

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ABSTRACT: Recent power quality measurement projects report that voltage sags are the most frequent disturbances in the sites [1]-[4]. DVRs were emerged as the best effective and economic solution for this problem [11]. This paper analyzed the power flow of a DVR in distribution grids. This paper showed various operation modes and boundaries such as inductive operation, capacitive operation, and minimal power operation beside the in-phase compensation.

Keywords: Power Quality, Grid, Power Electronics, Load Shedding, Reactive Power.

1 BACK GROUND

Power quality has been hot issue in the late half century [1]. Many power quality measurement projects which was done during from 1991 to 1993 by the Canadian Electrical Association (CEA) in Canada [2], during from 1993 to 1995 by the Electric Power Research Institute (EPRI) in USA [3], and during from 1996 to 1998 the DEFU in Denmark [4], report that voltage sags are the most frequent disturbances in the sites.

Typically in Denmark, one of the major causes of voltage sags seems "load shedding" operation that frequently occurs between the wind mill power generators or decentralized combined power plants with a grid. When a wind mill generator is connected to a grid to provide power, the grid voltage increases on the feeder. The other hand, when the wind mill generator is disconnected from the grid to cut out the power, the grid voltage decreases on the feeder. Decentralized combined generation system also causes same effects. An amount of 616 decentralized combined power plants were reported on 1999 in Denmark [5]. The number of the combined power plants increased more than 4 times during these 10 years. Each combined power plant seems to switch on/off more than two times a day [6]. Switching on the transmission levels also affects the distribution voltage level. The magnitude of the voltage variance is inversely proportional to the "short circuit level" of the grid [7]. Since the short circuit level of the grids in Denmark is decreasing according to the increase of the distributed power generators, these phenomena will be serious to the voltage quality in Denmark.

2 CHARACTERISTICS OF VOLTAGE SAG

The Danish Standard that follows CENELEC (EN50160-1994) standards defines very well about the sag and its indicative values [8];

Voltage dips (sags) are generally caused by faults occurring in the customers' installations or in the public distribution system. They are unpredictable, largely random events. The annual frequency varies greatly depending on the type of supply systems and on the point of observation. Moreover, the distribution over the year can be very irregular.

The duration and size of the sags are defined as 10[ms]–1[min] and 10[%]–90[%] respectively by the EN50160. The closest document to the standard is the CBEMA[3] curve that was originally developed by the Computer Business Manufactures Association and revised by the Information Technology Industry Council (ITIC) in 1996. The curve shows that the load sensitivity is very dependent on the duration of the sag.

While the CBEMA[3] limits suggest a "standard" sensitivity to voltage sags, actual plant equipment has a variety of operational characteristics during voltage sags. Malfunction occurs under 90% of RMS voltage in some equipment such as PLC (programmable Logic Controller), ASD(adjustable speed control drive). High-Intensity Discharge (HID) lamps are extinguished at around 80% normal voltage and require time to restart. Motor contactors usually drop out at 70% normal voltage. At lower voltages the display may not fill the frame and a dark margin becomes more visible [9].

Typical relationship between cost of damage caused by an outage in a typical MV distribution grid versus number of customers is inversely proportional [10]. The costs of a momentary interruption at a scale process line can be roughly assumed to be USD100,000 [11]. A sample inquiry carried out over a few years has provided an estimate of the financial prejudice of over FRF100,000 for the 17% of incidents that linked to short interruption in France [12].

It is well known that some voltage sags result from nature such as lightning, ice, and wind. Most voltage sags (60~90%) prolong under 15 cycles. Voltage sags usually occur in transmission lines, but should be compensated on distribution grids. The magnitude and duration of the retained voltage of the corresponding sags at the affected sensitive site are dependent on a number of electrical system variable such as the system capacity, location of the fault with respect to the affected site, and the system protection practices [13].

3 MITIGATION FOR VOLTAGE SAG

There are two general approaches to mitigate power quality problems. One is to ensure that the process equipment is less sensitive to disturbances, allowing it to ride through the disturbances. The other is to install a CUPS (custom power supply) device that suppresses or counteracts the disturbances. Many CUPS devices are commercially available in the market such as, active power filters (APF), battery energy storage systems

(BESS), distribution static synchronous compensators (DSTATCOM), distribution series capacitors (DSC), dynamic voltage restorer (DVR), surge arresters (SA), super conducting magnetic energy systems (SMES), static electronic tap changers (SETC), solid-state transfer switches (SSTS), static Var compensator (SVC), thyristor switched capacitors (TSC), and uninterruptible power supplies (UPS) [11]. DVR, that is a series-connected power electronics based device, is the best effective and economic custom power system (CUPS) to compensate for system sags and swells.

Because CUPSs are connected to the power system through distribution transformers, they are capable of operating at a variety of voltage rating from 400V to 20KV in Denmark. The DVR can be "partially rated" when compared to the load since the injected voltage can be less than the nominal line voltage. The use of a partially rated DVR may make for a more economical solution to a power quality problem, especially when the load exceeds several MVA. A number of other sag mitigation devices such as uninterruptible power supply (UPS) have to be rated to carry the full MVA rating of the load [14].

Many efforts have been done in analyzing and designing the series voltage compensators or dynamic voltage restorer (DVR)s. These works can be categorized into two parts; one is implementing a controller that has a good steady-state and a dynamic performance even if the systems are unbalanced and/or distorted by harmonics, the other one is finding control algorithms and/or circuit topologies which can minimize the active power consumption in the compensators to guarranty a long ride-through time with small energy storage elements. This is a minimal power compensation, while that is an in-phase compensation.

Under the in-phase compensation, the DVR is required to inject a certain amount of active power during the period of compensation [15]. Therefore, the stored energy becomes the limiting factor of the ride through time especially when the sags last longer. A principle of the DVR operation along with the DVR energy optimization was proposed [16]. The principle is based on the fact that the DVR can be successfully operated without using active power if the apparent power in the supply side is larger than the active power consumption in the load side. When the condition is fulfilled, the DVR just injects reactive powers to match energy conservatism between the source side apparent power and the load side active power. When the condition is not fulfilled, the DVR operates just in-phase compensation mode.

4 POWER FLOW ANALYSIS OF DVR

Fig. 1 shows the schematic one-line diagram of a grid system that is equipped with a DVR. The DVR has a large dc capacitor in the dc link to back up a necessary energy, and a matching transformer (MT) in the ac side to inject necessary ac voltages to the grid line. The load voltage V_L is required to be stable even when the source bus voltage V_S is varied.

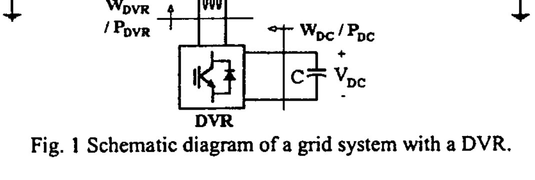


Fig. 1 Schematic diagram of a grid system with a DVR.

4-1 DC Link Capacitance

In the in-phase compensation algorithm, the MT must establish the same amount of the voltage sag in phased with the source voltage angle. The energy flows out from the MT during the voltage fault can be calculated as (1).

$$\Delta W_{DVR} = (1 - V_{sag}) \times I_S \times \cos\Phi_S \times \Delta t \qquad (1)$$

where, Δt : fault duration time, $\cos\Phi_S$: system power factor.

During a discharging, the DC link capacitor can provide energy as (2).

$$\Delta W_{DC} = \frac{1}{2} C \times \Delta V_{DC}{}^2 \qquad (2)$$

where, C : DC link capacitance, ΔV_{DC} : permissible DC link voltage ripple.

By the principle of energy balance, if there is no energy loss in the converter, following result comes out;

$$\Delta t = \frac{\Delta V_{DC}{}^2}{2(1 - V_{sag}) I_S \cos\Phi_S} C = \frac{\Delta V_{DC}{}^2}{2P} C \qquad (3)$$

For example, if the DVR must compensate 0.5 [sec] duration voltage sag of 80%, DC link capacitor must be more than 4.5 [F] when the permissible DC link voltage is 20 [%]. If the magnitude of the voltage dip decreases, this will becomes more larger.

Table I Typical example of voltage sag.

V_{sag} [pu]	I_S [pu]	PF $\cos\Phi_S$	ΔV_{DC} [pu]	Δt [sec]	C [F]
0.8	1.0	0.9	0.2	0.5	4.5

4-2 Compensation Without Energy Flow

Fig. 2 shows a space vector representation of some voltages to explain the minimal-energy compensation algorithm.

To compensate the voltage sag without using active power, following condition is necessary.

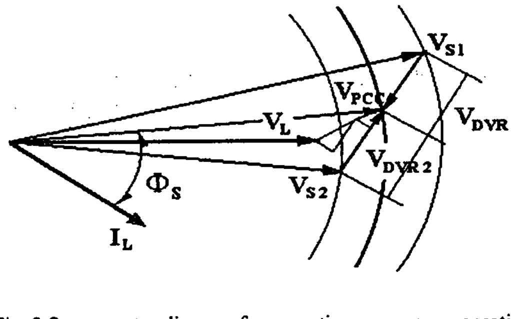


Fig. 2 Space vector diagram for a reactive power compensation strategy.

$$|V_S| \geq |V_L \cos\Phi_S| \quad (4)$$

When the angle of the DVR is controlled perpendicular to the phase of the load current as $\angle I_L \perp \angle V_{DVR}$ then no energy nor power flows from the DVR ie, $p_{DVR} = 0$. In this operation mode, the ride through time of the DVR can be infinite by a proper control.

4-3 Power Flow Analysis Of DVR

This paper analyzed a power flow of DVR in various operating conditions as follows;

1) Load power angle(ϕ_{LOAD}): 0° ~ 50°.
2) DVR phase angle(θ_{DVR}): -90° ~ 120°.
3) Magnitude of the faulted grid voltage(V_S): 50% ~ 140%.

Fig. 3 shows a set of power flow analysis results when 80% voltage sag was occurred. The horizontal axis is for DVR angles in degree. The vertical axis is for powers in p.u. The other axis that is perpendicular to both the horizontal and the vertical axes is for load angles in degree. Fig. 3(a) shows the apparent power flow. Definitely, the apparent power becomes minimized if the in-phase compensation algorithm is applied. Fig. 3(b) shows the active power flow. When the load angle is more than 40°, no energy flow operation mode seems possible with the DVR angles between 60° ~ 120°. Fig. 3(c) shows the reactive power flow. If the reactive power becomes positive, the capacitive operation of the DVR is possible. If the reactive power becomes negative, the inductive operation is possible.

Fig. 4 shows the operation boundaries for the minimal-power compensation in several cases of voltage sags or swell. Fig. 5 shows the operation boundary surface for the inductive-capacitive operation modes. Fig. 6 shows the possible operation area for the zero-active power (without energy flow) operation. Fig. 7 shows the saving of the active power in the minimal-power compensation algorithm, which can increase the ride through time of the DVR. Fig. 8 shows a simulation result to verify the proposed theory.

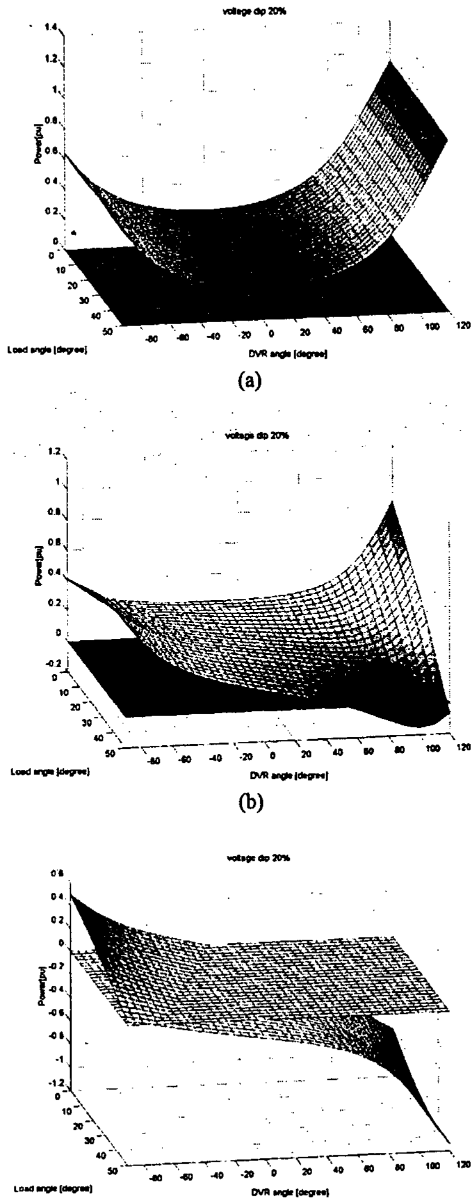
5 CONCLUSION

This paper provided analysis method and data for the power flow analysis of a DVR in various operating conditions. Analysis results showed various operation modes of a DVR can be possible:

1) Inductive operation mode.
2) Capacitive operation mode.
3) Minimal active power operation mode.

With the inductive operation mode of a DVR, the line inductance will be increased so that the short current from the load fault may be attenuated. Conversely with the capacitive operation mode of a DVR, the line impedance will be decreased to reduce the voltage drop of the grid. Thirdly with the no active power operation of a DVR, the ride through time of the DVR will be increased using just a small dc capacitor as an energy storage element.

Research is still going on for the design of the controller for the three operation modes.



(a)

(b)

(c)

Fig. 3 Power flow analysis when 80% voltage sag occurred; a) apparent power, b) active power, c) reactive power.

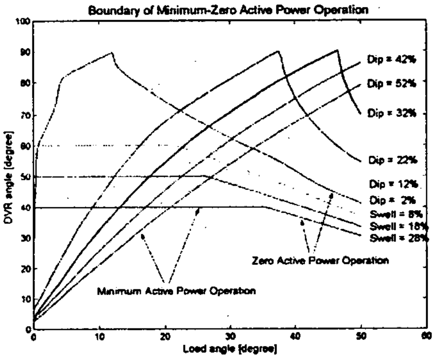


Fig. 4 Operation boundary of Minimal Power Operation.

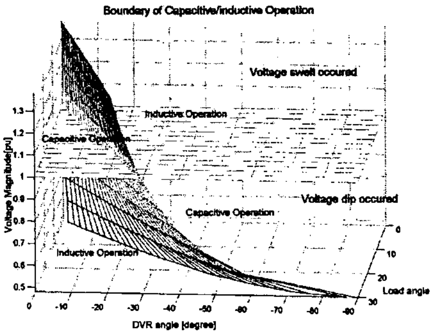


Fig. 5 Boundary for Capacitive/inductive operation.

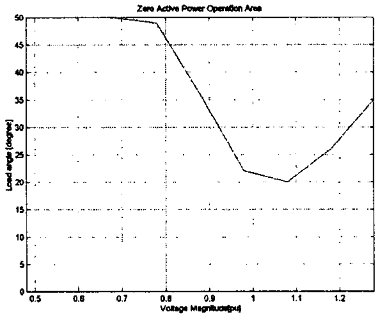


Fig. 6 The operation area of zero-active power flow.

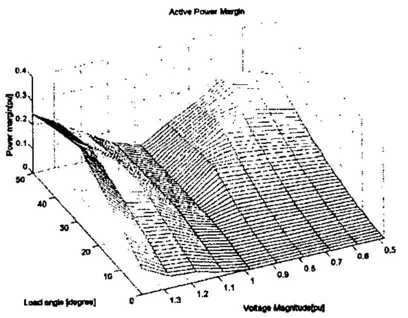


Fig. 7 The difference of active power flow between the two control algorithm; in-phase compensation and minimal-power compensation.

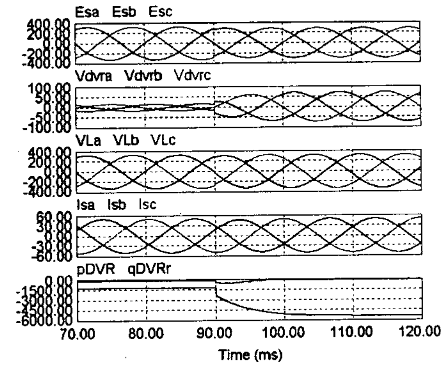


Fig. 8 Simulated waveforms; voltage dip=12%, Load power angle=40 °, DVR angle(θ_{DVR})=60 °.

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