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A step-dynamic voltage regulator based on cascaded reduced-power series transformers

M.E.C. Brito [a], L.R. Limongi [b], M.C. Cavalcanti [b,*], F.A.S. Neves [b], G.M.S. Azevedo [b]

[a] *Companhia Energetica de Pernambuco (CELPE), Recife, Brazil*
[b] *Federal University of Pernambuco, Department of Electrical Engineering, Recife, Brazil*

A R T I C L E I N F O

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ABSTRACT

The large number of computers and other sensitive electrical loads connected to power grid are directly affected by grid disturbances. The vast majority of these disturbances is related with voltage transients, such as voltage sags. This paper deals with a step-dynamic voltage regulator designed to protect the load against the effects of these voltage transients. The ideia is to use a simple structure based on the insertion of a cascaded reduced-power series transformers between grid and load. It makes possible the use of actual mains voltages to compensate and mitigate the disturbances. It will be shown that the proposed solution can fully compensate or mitigate the faults that occur more frequently in power systems. Experimental results obtained on a 5 kVA prototype demonstrate the feasibility of the proposed solution.

1. Introduction

The short-duration voltage variations are the most frequent and significant disturbances present in the power grid and they are largely responsible for unplanned shutdowns in industry. It is often caused by system faults, switching of large loads which require high starting currents, or intermittent loose connections in power wiring [1]. Depending on the location and the system conditions, the fault can cause temporary voltage rises (swells), voltage dips (sags), or a complete loss of voltage (interruptions) [1,2]. The vast majority (92–98%) of these disturbances are voltage sags [3] and power utilities have faced an increasing number of occurrences related to it [4,5]. The large number of computers and other electrical loads connected to power grid are at the heart of the problem [6]. The control of large industrial processes is performed by computers that usually present malfunction during a failure in the power system. Therefore, a voltage sag has a considerable impact on production, since the time expended to perform a complete restart of the process after a system fault is usually long [1].

The dynamic voltage restorer (DVR) is a device designed with the primary function to compensate voltage sags and swells [7–9]. However it can also be designed to perform additional features such as reducing the transient voltages as well as voltage harmonics, protecting sensitive loads from unexpected shutdowns and malfunction due to power quality degradation produced by these phenomena. The traditional scheme of a DVR consists of an inverter connected in series to the grid through a coupling transformer as shown in Fig. 1 [9]. So, hereinafter it will be called inverter-based DVR. During the disturbance, the inverter-based DVR injects the compensation voltages in real time, protecting the load against failure. There are several derivations of this topology proposed in the literature [9–15]. In Ref. [9], an arbitrary type of energy storage is used to feed the dc link. In Ref. [10], the active power to compensate the voltage sag is taken from the incoming supply through a passive shunt converter connected to the supply side. In Refs. [11–13], the inverter-based DVR is implemented using multilevel converters. These topologies have a common characteristic: they are relatively expensive systems because of the inverter that includes energy storage elements and power switches.

On the other hand, a great effort has been made to reduce costs. In Ref. [16], it has been presented a inverter-based DVR based on direct converters without energy storage elements. Another alternative based on a single-phase direct ac/ac converter energized from the main grid is proposed in [17]. In Ref. [18], the inverter-based DVR topology allowed the use of high frequency transformers with the benefit of reducing size, weight and cost of the whole structure. Nevertheless, these topologies are still based on complex power switches systems and powerful computational platforms. This is because most inverter-based DVR topologies are designed to compensate the voltage sag in a small fraction of a voltage cycle. However, taking a careful look at the Computer Business Equipment Manufactures Association (CBEMA) and Information Technology Industry Council (ITIC) curves, that establish the susceptibility levels of the sensitive electronic equipment [1,19], it is possible to

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* Corresponding author. Tel.: +55 81 21267102.
E-mail address: marcelo.cavalcanti@ufpe.br (M.C. Cavalcanti).

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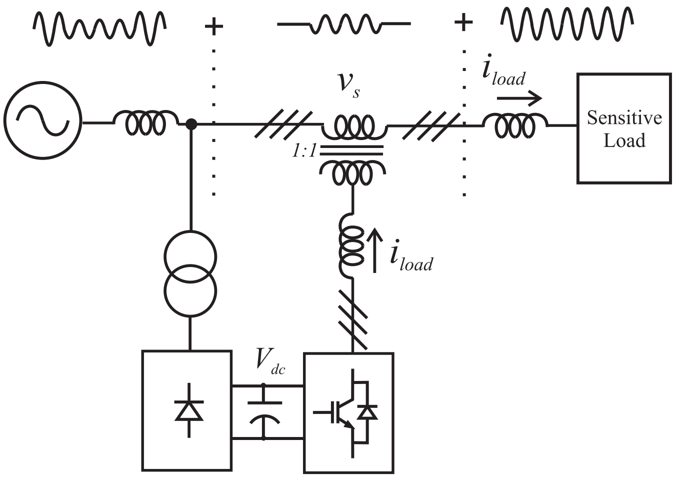

Fig. 1. Traditional inverter-based DVR topology.

note that the transient response does not need to be as fast as the state-of-art DVRs are. The same assumption is also valid for the voltage compensation limits. In other words, it is possible to choose the inverter-based DVR compensation limits nearer to the CBEMA and ITIC curves and still protect the sensitive load. Therefore, these characteristics can be exploited to obtain an alternative in terms topology.

Some topologies known as dynamic voltage regulators, based on electromagnetic devices, were proposed more than two decades ago. In general, these proposals are very simple in terms of implementation needs but present some important drawbacks. In Ref. [20], thyristors are used to deliver a voltage waveform to the load which is in quadrature with the grid phase voltage. The resulting load voltage is then distorted by the compensating device and it cannot be used as a steady-state compensation device. Another scheme was presented in [21] through the use of thyristor-controlled multi-tap transformers, similar to the topology shown in Fig. 2. However, the voltage regulator has some drawbacks that do not allow its utilization to compensate sags: the need to pass through intermediate stages, i.e., it is not possible to go from tap 1 to tap 3 without passing through tap 2, making the equipment too slow for complying with the current grid codes; the number of bidirectional switches to be used must be equal to the number of steps of the compensating device; all switches must have full current conduction capability.

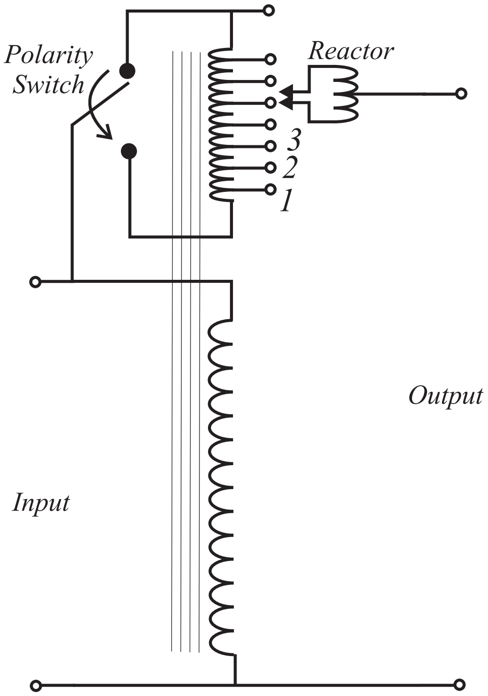

Fig. 2. Voltage regulator.

A low cost topology can be achieved through a step-dynamic voltage regulator (S-DVR) that uses the actual mains voltages to compensate and mitigate the disturbances [23–32]. Therefore, it is not necessary to use inverter systems and energy storage elements to synthesize a sinusoidal voltage making the solution very simple in terms of implementation. This topology has been originally proposed by the authors in [33,34], with the main focus in the costs analysis of the proposed scheme using thyristors devices.

Related to the previous versions [33,34], the main contribution of this paper is the presentation of experimental validation of the proposed topology. This is important in order to show that equipment time response is short enough to comply with CBEMA and ITIC curves [1,19]. In the previous papers, there were only some results related to the control board performance with no test bench. Furthermore, this work presents some design aspects regarding the transformers and switches of the proposed topology; and a cost comparison considering the proposed topology (using bidirectional switches) and the inverter-based DVR. In order to avoid using market-dependent values, the components have been characterized by the power handled by them. After a thorough bibliographical research, it can be stated that although being simple the proposed topology is innovative and has a good potential for being accepted in industry due to its good performance and low cost.

2. Voltage sags and equipment susceptibility considerations

Most of the voltage sags are caused by short-circuit faults many of them last only a few tens or hundreds of milliseconds and are unbalanced (i.e., involve a negative-sequence component [3]). When a fault occurs at some point in the power system, the voltage drops until a protection trips to clear this fault. During this interval, all loads that are connected at the faulted feeder will be subjected to a voltage sag.

The five types voltage sags that can commonly be experienced are A, B (one-phase sag, no phase shift), C, D and E (two-phase sag, no phase shift). For type A voltage sags, the three-phase voltages are balanced, while the phase voltages are unbalanced for type C or D voltage sags, as shown in Fig. 3. The type A voltage sag is produced by a three-phase fault, and it is characterized by the same voltage drop in all three phases. The type D voltage sag appears on the secondary side of a distribution transformer with delta/wye connection and having its primary side subjected to a phase-to-phase fault. A type C voltage dip may occur in any of the following two situations: (1) a phase-to-phase fault at the transformer secondary side or (2) a single-line-to-ground fault in the transformer primary side (seen as phase-to-phase fault at the secondary side).

There are many international standards that classify the voltage sags, such as IEEE 1159 [2], which defines voltage sags as events that have duration shorter than one minute during which the rms voltage is lower than 0.9 p.u. Although the standard sets limits, it does not address the susceptibility levels for the sensitive electronic equipment. However, some consensual curves do exist like CBEMA and ITIC [1,19,22] which establish voltage limits for the safe operation of industrial equipment. Based on the ITIC curve shown in Fig. 4 some considerations can be made: