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Voltage conditioner & power flow controller based on bipolar matrix-reactance choppers

Jacek Kaniewski, Paweł Szcześniak *, Marcin Jarnut, Zbigniew Fedyczak

University of Zielona Góra, Institute of Electrical Engineering, Str. Podgórna 50, 65-246 Zielona Góra, Poland

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ABSTRACT

Voltage amplitude is one of the most important parameters of electrical energy, particularly from the viewpoint of sensitive loads connected to the grid. The dynamic state in a power grid (voltage sags/swells/interrupts) originating from dynamic loads, uncontrolled power flow, switching effects, adverse weather condition, etc., might cause defects in sensitive loads and financial losses. The annual damages in Europe due to voltage perturbations is estimated at 10 billion €. This paper presents a three-phase voltage conditioner and power flow controller without DC energy storage unit for the control of phase and voltage amplitude. In comparison to conventional solutions, such as DVR or UPFC, the power electronic AC/AC converter is based on a bipolar matrix-reactance chopper. The main aim of this paper is to analyse the basic properties of the presented solution, especially from the point of view of the ability to compensate voltage sag/swell and interruption and to control phase shift in bidirectional power flow control. The studies have been carried out on a three phase system with passive and active load (two-source system). On the basis of the authors' research, it can be stated that the described solution gives the possibility to compensate deep voltage sag (50% of nominal voltage), overvoltages (up to 150% of nominal voltage) and single phase interruption. Simultaneously the solution allows independent control of the phase angle of output voltage in the range ± π/3. The paper presents an operational description, theoretical analysis, simulation and the experimental test results of a 1 kVA laboratory model using a conventional PWM control strategy.

1. Introduction

The voltage perturbations in the power system, such as voltage dips/swells, interruption, voltage imbalance, and flicker effect are caused by dynamic loads (electric drives with heavy start, electric welding devices, etc.) and switching effects (the operation of the power grid, changing of the transformer taps, etc.). Additionally, voltage perturbations are caused by accidents and adverse weather conditions (atmospheric discharge, wind, temperature changes, etc.) (Fig. 1) [1,2]. Another cause of voltage perturbations, especially flicker effect, are uncontrolled power flows in the power system. These power flows are due to the operation of distributed energy sources (turn-on/turn-off), especially renewable energy sources connected to the grid [3,4]. In the case of renewable energy the output power is strongly dependant on the condition of the source energy (wind, sunshine, etc.).

Voltage amplitude is one of the more important parameters of the power quality issue. In the case of AC voltage supply perturbation, there is a high risk of faulty operation or damage to devices which are sensitive to voltage changes, such as adjustable speed drives, AC-contactors, lighting loads, electric vehicle chargers, etc. [5–7]. Moreover the voltage perturbations generate high financial losses. The annual financial costs in Europe due to voltage perturbations, especially voltage sags and interruption, is estimated at 10 billion € [8] while cost of preventative measures is less than 5% of this [8,9]. More than 55% of this cost is generated in the industry sector, 32% in commercial, and More than 9% in the public sector [10]. The cost of one event, depending on the type of industry, is estimated at 250,000 € and even up to 3.8 mln € in the case of semiconductor production [8]. Similar values are reported in investigations conducted in the USA [11]. Bearing in mind the above, voltage perturbation is not just a technical problem, but currently a techno-economic problem.

Considering the above there are two paths leading to the protection of sensitive loads against voltage perturbation and the reduction of financial losses caused by voltage perturbation. The first-one is to increase the ride-through capability of electrical

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* Corresponding author.

E-mail addresses: j.kaniewski@iee.uz.zgora.pl (J. Kaniewski), p.szczesniak@iee.uz.zgora.pl (P. Szcześniak), m.jarnut@iee.uz.zgora.pl (M. Jarnut), z.fedyczak@iee.uz.zgora.pl (Z. Fedyczak).

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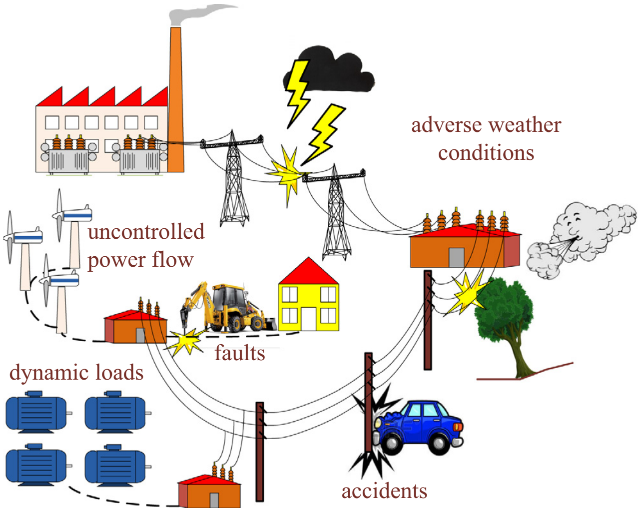

Fig. 1. Main reasons of voltage perturbations in AC power system.

devices during voltage perturbation [12,13]. The second-one is the implementation of voltage conditioners to mitigate voltage sags, swells and interrupts. Both means should be developed simultaneously and independently.

There are numerous different solutions and topologies of voltage conditioners, also called voltage compensators. A very popular group of devices is based on AC/DC/AC or DC/AC converters with DC energy storage, such as DVR [14] or STATCOM [15]. However, the DC energy storage element implemented in converters with DC link is the main factor contributing to their size and weight, and it is an expensive element which is very frequently damaged in operation [16]. Moreover, the solution described in [15] is a shunt connected to the grid. The range of voltage change is limited by the permissible load of the transmission line to a few percent of nominal voltage. Another popular group of voltage compensators is based on direct AC/AC converters without DC energy storage (matrix and matrix-reactance choppers, matrix converters) [17–29]. Additionally, this group can be divided into two other groups: with galvanic separation between source and load [18,19,21,22,24] and without galvanic separation [17,19,20,23,25,26–29]. Galvanic separation is a crucial issue in power system applications, especially from the point of view of safety and matching of voltage level in the power grid. However despite the many advantages, the voltage compensators with galvanic separation usually require a transformer with additional windings, and must be oversized. Moreover the voltage compensators based on AC/AC converters without DC energy storage usually operate in in-phase/anti-phase mode [17–20,22,25,28,29] to compensate voltage sags or swells. Yet, voltage amplitude control only, in some cases, is not enough, especially if voltage perturbations are caused by dynamic power flow between two areas of the power grid. The devices described in [21,23,24,26,27,30] allow for control of amplitude and phase of voltage simultaneously and independently. However these solutions have a more complex structure. The hybrid transformer described in [21] guarantees good dynamics and a wide range of voltage control, but requires a matrix frequency converter (MFC) to realize voltage phase and amplitude control. Moreover, this transformer requires additionally secondary windings to supply the MFC. The controllable network transformer with an AC/AC converter (called "thin AC converter") to control voltage amplitude and a power flow is presented in [24]. An interesting solution with the ability to compensate deep voltage sag is presented in [25], and developed in [26] by improving the properties for voltage phase angle control. However to operate as a phase shifter additional switches in the structure of the AC/AC converter are required [26].

The main aim of this paper is to present the concept and main properties of a new topology of the three-phase voltage conditioner based on direct AC/AC converter without DC energy storage, to control amplitude and phase angle of voltage simultaneously and independently. These properties present an opportunity for the implementation of this circuit as a power flow control and voltage regulator in transmission lines. This paper develops the concept described in [26] by replacing the AC/AC converter with additional switches by bipolar matrix-reactance chopper [23]. Moreover the presented results are extended by a more detailed theoretical analysis based on the averaged space state method and four terminal description. Additionally, the results of experimental tests on a 1 kVA laboratory model are presented for two variants: with passive load and with active load. The presented solution can operate in two control modes: in amplitude control mode (only amplitude of output voltage is controlled), and in phase and amplitude control mode (both values – phase angle and amplitude of output voltage are controlled independently).

2. Circuit and operation description

2.1. The main circuit

The main circuit of the considered three-phase voltage conditioner and power flow controller (VC&PFC) is shown in Fig. 2. The described voltage conditioner is a kind of series device such as a conventional DVR [14] or UPFC [28].

The main parts of the presented solution (Fig. 2) are direct AC/AC converters (AC/AC I, AC/AC II, AC/AC III) operating in each phase. Converter AC/AC I operates on line L_1, but is supplied from two other lines (phases) – from line L_2, and L_3. Analogously, converter AC/AC II operates on line L_2, but is supplied from lines L_1 and L_3, and in the case of converter AC/AC III – it operates on line L_3, but is supplied from lines L_1 and L_2. Each AC/AC converter consists of two bipolar matrix-reactance choppers (MRC) Ćuk B2 type [29] (Fig. 2). The MRC's are controlled via a conventional PWM control strategy, where the modulated signal (triangle) is compared with the modulating signal (constant signal) (Fig. 2). The outputs of MRC 1 and MRC 2 are connected to the primary side of the transformers TR1 and TR2 respectively. For better operating conditions during voltage sags, the secondary voltages of TR1 and TR2 ($n\underline{U}_{MRC1}$ and $n\underline{U}_{MRC2}$) are in opposite phase in relation to primary voltages ($\underline{U}_{MRC1}$ and $\underline{U}_{MRC2}$). The secondary sides of TR1 and TR2 are connected in series (Fig. 2). The voltage ratio (polarity) of transformers TR1 and TR2 is equal "-1" (nTR1 = nTR2 = $n = -1$). Transformer Polarity refers to the relative direction of the induced voltages between the primary voltage terminals and the secondary voltage terminals. It means that the secondary voltage of the TR is in opposite phase in relation to primary voltage. The Ćuk B2 MRC is called bipolar, because the output voltage of the MRC used could be in phase or in opposite phase (shifted by π) in relation to input voltage. Moreover MRC used has buck-boost character. This means that the output voltage of the MRC could be lower or higher than the input voltage. The idealized voltage transmittances of Ćuk B2 MRC's operate in phase one and is described by (1) and (2) [31,32].

$$|\underline{H}_U^{MRC1}| = \left|\frac{\underline{U}_{MRC1}}{\underline{U}_{S2}}\right| \approx \frac{(1-2D_1)}{(1-D_1)}, \tag{1}$$

$$|\underline{H}_U^{MRC2}| = \left|\frac{\underline{U}_{MRC2}}{\underline{U}_{S3}}\right| \approx \frac{(1-2D_2)}{(1-D_2)}, \tag{2}$$

where D_1, D_2 – pulse duty factors respectively of MRC 1 and MRC 2. Bidirectional power electronic switches (S1, S2 and S3, S4) in each