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Grid-connected converter active and reactive power production maximization with respect to current limitations during grid faults

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ABSTRACT

During the grid disturbances, particularly voltage sags, if the grid-connected converter's (GCC's) power references are kept at the pre-fault level, the excessive currents would flow. This could force the inverter disconnection, which is in conflict with the grid codes and the tendency to keep the GCC system connected to the grid as long as possible. Keeping the system connected for a prolonged periods of time offers a possibility of a more effective grid support, better exploitation of available energy resources and generally more reliable power supply. The aim of this paper is to address the utilization of active and reactive power production capacities during unbalanced voltage sags with respect to the current limits. First proposed algorithm gives the grid operator the opportunity to choose whether active or reactive power production is prioritized during voltage disturbance, with the curtailment done only to the extent that the current limits are not surpassed. Second approach allows for the power factor to stay the same before and during the sag. Selected hardware-in-the-loop experiments are presented to validate the developed theoretical background and implemented algorithm.

1. Introduction

Grid-connected converters are affected by grid disturbances, particularly when connected to the distribution power grids and microgrids, as they tend to be less stiff and prone to irregularities. With further proliferation of distributed energy sources based on GCCs, the associated grid interconnection problems will be amplified if not addressed properly [1]. On the other hand, the grid codes demand ever increasing grid support from these units, even in cases of pronounced grid faults [2].

Voltage sags are particularly important disturbances to be addressed, as they are the most frequent and can have the most adverse effects on the GCCs' operation. The main reasons for the unbalanced voltages occurrences are short-circuit faults, connection of the big loads and unbalanced loads [3]. The first two often result in a transient, short-lasting, still more serious dips. The load unbalances, intrinsic characteristic of the distribution networks, usually result in less pronounced, but significantly longer-lasting dips. In any case, the longer the converter can safely stay connected to the grid the better. If the voltage sag is serious, the grid support realized by the production of reactive power could have strong palliative influence during and post-fault. On the other hand, if the voltage dips last longer, inadequate control strategies could lead to poor utilization of available energy supplied by the primary energy sources, to load shedding etc. Furthermore, keeping the same power references as before the fault will cause excessive currents that will lead to triggering of the unit's protection and disconnection from the grid - trait especially pronounced in cases of asymmetrical voltage dips. Therefore, flexible GCC control algorithms that secure safe and maximized power production are of great importance for future power systems.

A number of control strategies with flexible current and power production have been developed. Still, safe production, with respect to the current limitations, imposed by the converter switching elements' characteristics, has seldom been discussed.

Until recently, the grid codes did not require photovoltaic based distribution generation units to offer grid support and, consequently, generate reactive power during voltage sags, but were expected to produce active power. As a consequence, safe power production strategies were proposed, but only with respect to the active power [4–7]. Some grid codes now demand a grid support feature from PV applications and thus the previous references become obsolete [8]. Unlike in PV applications, in wind farm and static compensator applications, only reactive power is of interest during deep voltage sags [9–11]. The approach proposed in [12,13] addresses not only current amplitudes, but also comprehensively examines safe power production possibility considering the AC and DC side voltage limits. Furthermore, load balancing feature is introduced. Still, this algorithm also takes into account only the reactive power. Again, dedicated solutions could become outdated

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and would not suffice if the grid codes are changed [14]. Having the possibility of fluid change in power production at disposal would be in the accordance to the tendency to make the grid more flexible and responsive to different fault scenarios. Also, the fact that one-sided approach was assumed limits the number of applications in which the proposed solutions can be applied.

The paper [15] does offer the simultaneous active and reactive power production, but it does not account for the negative sequence current components. Thus, this oversimplified solution results in non-sinusoidal currents and uncontrolled oscillations in active and reactive power. The solution proposed in [14] gives general approach to the problem of the power references calculation in the stationary reference frame. This should be the base for the flexible peak current limitation solution for different power curtailment scenarios. Still, final algorithm output manages only average components of active and reactive powers. Oscillating components were not taken into account. Also, in order to function properly, the proposed algorithm necessitates usage of the sag detector. The sag detector's dynamics certainly has a degrading effect on transient processes. Furthermore, for the reactive power reference calculation, active power reference, that is the output of the higher-layer control loop, is used (and vice versa). It could happen that this active power reference alone would result in currents that are above the limits. This situation was not addressed and thus the expressions for the references would become unsolvable. A similar remark can be made for the approaches given in [16,17]. The appropriate curtailment of the power reference that comes from the higher-layer level loop was not considered. The results supplied in [18] suggest that the current capacities are not fully used as currents' amplitudes are well under the limit. Also, the currents have highly non-sinusoidal waveforms.

This paper proposes contemporary calculation frame that yields maximized converter utilization both in regular and irregular grid states, taking into account different grid support strategies, currently valid and beyond standards. The algorithm shown here offers two paradigms with total of six possible scenarios for safe simultaneous control of active and reactive power flow with certain distinctive features. The first paradigm corresponds to the scheme of output power maximization while giving production priority to the active power or reactive power. The second paradigm corresponds to the scheme of output power factor control, again with maximized total power output. In both paradigms, active or reactive power oscillating components at double the grid frequency are optionally minimized. Minimized active power oscillations would lead to minimized oscillations in the DC link voltage, while minimized reactive power oscillation could be of primary interest because of AC side voltage stability. Next, the algorithm does not require a sag detector. Thus, during algorithm execution, there is no need for the code structure change. The transition from nominal condition to the fault-ride-through regime progresses seamlessly, implying the best possible transient behavior. Furthermore, the produced grid currents have sinusoidal shape and are limited at exactly the set maximal value. This guarantees, on the one side, maximal power production, and, on the other side, safe operation of the converter and prevention of overcurrent tripping. The above stated features apply all down to the complete voltage collapse. Finally, the algorithm was set up to suit practical implementation on a dedicated microcontroller regarding structural and computational burden.

The paper documents all theoretical and implementation aspects of the algorithm structure and is organized as follows. Section 2 describes the underlying current control algorithm.

In Section 3, the current references calculation scheme that fulfills respective control and functional objectives is introduced. Section 4 presents selected HIL experimental results obtained on the hardware-in-the-loop experimental laboratory setup and provides discussion on feasibility and effectiveness of the proposed control strategies. Finally, Section 5 gives concluding remarks and proposes possibilities for future research.

2. Grid-connected converter control algorithm

The connection of renewable energy sources to the existing power grid has become an interesting and challenging task for researchers in recent years, especially when the disturbances are taken into account. As a result, a number of inverter control strategies that ensure safe and reliable power production even with the perturbation in the grid have been developed. Most of the strategies are based on symmetrical components extraction [19–21]. Those based on direct power control [22,23] and sliding mode control [24] have also been examined and successfully validated. A thorough overview of these control strategies and other less common approaches can be found in [25–27].

Algorithms based on symmetrical sequences extraction employ either the proportional-integral (PI) or the proportional-resonant (PR) controllers. PI current regulators face the existence of the ripple at double the grid frequency caused by inversely rotating current and voltage components [28]. This poses fundamental constraint upon the attainable control bandwidth. On the other hand, the ability of a PR controller to control oscillating variables in their original form obviates the need for filtering and simplifies the design of the loop dynamic characteristics [29]. Still, it is less intuitive and harder to analyze the alternating variables in stationary reference frame and the process of references calculation is a more straightforward task in synchronous reference frame.

As both aspects - control dynamics and handling the references - are crucial for attaining control goal, the approach taken here was to combine the control methods - PR regulators were used for the current control, with the references calculated in the synchronous reference frame. The outlook of the plant and control algorithm is illustrated in Fig. 1. Measured three-phase grid currents, i_{abc}, and grid voltages, u_{abc}, are first transformed to the two-phase stationary $\alpha\beta$ system by using Clarke transformation. The transformed voltages, $u_{\alpha\beta}$, are fed to the-sequence extractor and phase-locked-loop (PLL) unit that calculates synchronous frame grid voltage components, u_{dp}, u_{qp}, u_{dn} and u_{qn}, estimated grid angle, θ, and frequency, ω. This stage is based on the dual second order generalized integrator [30]. Active power reference, P^r, is usually produced by the DC-link voltage controller. According to the [31,32], the reactive power reference is generated by either grid voltage control loop, can be specifically defined by the grid operator in VAr or can be calculated using defined cosφ and available active power. Power references, grid voltage sequences and angle are used in the process of current references calculation. The transformation of positive (p) and negative (n), direct (d) and quadrature (q) current reference components, $i_{dp}{}^r$, $i_{qp}{}^r$, $i_{dn}{}^r$ and $i_{qn}{}^r$, into the stationary reference frame is done according to inverse Park transformation (1) [33].

$$\begin{bmatrix} i_\alpha^r \\ i_\beta^r \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{dp}^r \\ i_{qp}^r \end{bmatrix} + \begin{bmatrix} \cos(-\theta) & -\sin(-\theta) \\ \sin(-\theta) & \cos(-\theta) \end{bmatrix} \begin{bmatrix} i_{dn}^r \\ i_{qn}^r \end{bmatrix} \tag{1}$$

After the expression (1) is reorganized, the expressions for stationary reference frame components, $i_\alpha{}^r$ and $i_\beta{}^r$, are obtained.

$$i_\alpha^r = (i_{dp}^r + i_{dn}^r)\cdot\cos\theta - (i_{qp}^r - i_{qn}^r)\cdot\sin\theta \tag{2}$$

$$i_\beta^r = (i_{dp}^r - i_{dn}^r)\cdot\sin\theta + (i_{qp}^r + i_{qn}^r)\cdot\cos\theta \tag{3}$$

Finally, according to the current references, PR regulators control the actual currents by providing corresponding inputs to the space-vector modulator.

3. Current references calculation scheme

The grid current references can be calculated using the system of equations that stem from the expression for the apparent power expressed in complex notation:

$$\hat{S} = P + iQ = (e^{i\omega t}u_{dq}^p + e^{-i\omega t}u_{dq}^n)\cdot(e^{-i\omega t}i_{dq}^{p^*} + e^{i\omega t}U_{dq}^{n^*}) \tag{4}$$