Protective Controller against Cascade Outages with Selective Harmonic Compensation Function

B N Abramovich, P A Kuznetsov, Yu A Sychev
Saint-Petersburg Mining University, 2, 21 Line Ave., St. Petersburg, 199106, Russia
E-mail: kuznetsovpavel@inbox.ru

Abstract. The paper presents data on the power quality and development of protective devices for the power networks with distributed generation (DG). The research has shown that power quality requirements for DG networks differ from conventional ones. That is why main tendencies, protective equipment and filters should be modified. There is a developed algorithm for detection and prevention of cascade outages that can lead to the blackout in DG networks and there was a proposed structural scheme for a new active power filter for selective harmonics compensation. Analysis of these theories and equipment led to the development of a protective device that could monitor power balance and cut off non-important consumers. The last part of the article describes a microcontroller prototype developed for connection to the existing power station control center.

1. Introduction
Modern society, industry and infrastructure need electricity for supporting normal everyday life and economical wellbeing. Due to political relations, climate conditions and because of fossil fuels petering-out, there was a developed tendency to use more renewable energy resources. For power systems it is evident that the number of integrated generating devices will only increase with time, and conventional power networks, made according to the “Generator-Network-Consumer” scheme, will be transformed and modernized to the DG networks level.

Also, it is worth mentioning that generator’s models that cooperate with renewables sources, their control and switching schemes, load cycles and control algorithms differ significantly from conventional ones [1]. Any deviations in supplied frequency between source and receiver in balanced and synchronized system can be compensated initially in kinetic energy changes of the coupled generators and motors. In order to provide stability, power network frequency must always be supported between the previously defined measures. This can be achieved with the installation of different compensating and balancing devices during short time.

Three main disbalance reasons in power networks can be sectioned out after short failures analysis. First of all, these can be emergency modes that are connected with outages in generators, consumers or elements of distributed networks. The second group of problematic reasons unites all failures and inaccuracies connected with generation’s regulation functions and control algorithms related to load. The third group contains prognosis mistakes for generators and consumers. Integration of a big number of generators, which are connected with renewables will only increase the number of mistakes and failures in the existing networks due to different operation mechanisms. This fact testifies that nowadays the task to provide robust power quality in DG networks comes to the first place.
The research [2] contains prototype’s development of improved Active Power Filter for harmonics compensation from renewables’ converters and consumers’ semiconductor electronics. Also, some authors [3,4] describe different developments and prototypes of modernized units for power quality improvement. The main tendency that unites all these and other modern researches is refusal from classic theory of power compensation and implementation of instantaneous power theory [5]. Hence, all these facts testify that it is necessary to develop an effective microprocessor system for power quality improvement and cascade outages (blackouts) reduction with implementation possibility into DG-networks.

This paper presents an investigation of the development of cascade outages and blackouts in DG-networks and compares it with conventional ones and proposes new filtering technique together with protective device against cascade outages.

2. Cascade outages development algorithm in DG networks

With the growing number of electric vehicles and small generators based on renewable sources, power networks started to transform their structure from centralized to decentralized schemes. Moreover, implementation of renewable generators in huge amounts create a whole new research branch in power quality science in order to study different transient modes and processes in DG-networks. One of these cases can be studied by the example of German networks [6]. Big investments were made in order to integrate PV and wind power stations in conventional power grids. However, they were not prepared for such big amount of DG-sources. Nowadays some of them work only with 30-50% useful load because gas turbines at a big power plant cannot react quickly to fast-changing load. Also power quality problems became extremely important due to big harmonics generation from power converters.

All these fast-changing processes in power balance combined with distorted waves’ forms can lead to appearance of power disbalance and, as a result, emergency modes. The last ones may and often evolutionize into cascade outages and blackouts. There was a conducted research and there was a modernized algorithm proposed in [7], which shows initiation and development of blackout. It is shown in figure 1. As compared to its original version, there were made corrections for DG networks.

![Figure 1. Blackout development in DG power networks](image)

According to this algorithm, main distinctions in emergencies behavior can be formulated.
A reliability question. From the first look, it seems that DG networks are more robust against cascading outages because they keep faster performance, reserves and inner interconnections. However, more detailed analysis demonstrates that a greater number of rectifiers, converters, non-linear loads, switching and transient modes, presence of harmonics sources make them more vulnerable and their synchronisation and normal operation tasks more complicated.

The post-shutdown start process. After degeneration to the islanded parts level, the DG network is theoretically easier to start up. It is known that starting currents can exceed their operating value more than 5 times. This problem is also important in conventional grids, where cold start up is made step-by-step with gradual load connection. However, due to a lot of relays, converters, protective equipment in DG networks and the fact that each islanded part can operate with its own frequencies deviation and do not be synchronized with others, DG-network start up can be even harder.

The power quality problem. According to the certification documents [8], the harmonics number at the consumer’s side can be much higher in DG networks. That is why protective units should have different operating algorithms due to other nature of parasite currents [5].

3. Active Power Filter for selective harmonics compensation

As it can be seen from the algorithm, harmonic components from non-linear loads in DG networks imply the cascade outages development, despite the fact DG-networks sustain emergency modes better. Due to this fact, a task appears to implement modernized Active Power Filters (APF) in order to compensate harmonics selectively.

One of the potential units is a modernized APF with selective compensation of current harmonics based on a three-phase multilevel NPC converter. Its structural scheme is shown in figure 2. The proposed design possesses an excellent possibility to decrease individual current harmonics or certain harmonic groups increasing power quality. This improves THD. Multilevel topology simplifies its application in power quality units on the distribution and transmission levels. In addition, it is possible to implement a filter in the reactive power compensation equipment that corresponds to [2,5]. A selective compensation function allows APF to use all the available power for harmonics compensation with a huge THD increase.

Figure 2. Topological scheme of APF with Multilevel Converter

Harmonics in load current are normally detected with the synchronos rotary frame (SRF) technique and a low frequencies filter (LFF) (see figure 3). Hence, in harmonic reference frame $d-q$ only selected harmonic is a DC-signal. All other frequencies, including nominal ones, represent AC-signal. LFF is used to delete all these AC-signals, filtering only a DC-signal that of interest as harmonic current. Filtered $d-q$ harmonic current from the load and the converter is then sent to the PI-controller. This controller generates harmonic currents with equal magnitudes. The same amplitudes have currents, generated with non-linear loads, but with the opposite polarity. Hence, it is possible to compensate harmonic currents from non-linear loads with the help of converter’s harmonic currents in the point of
common coupling.

\[ V_{abc} \]
\[ V_{dc} \]
\[ i_{abc, inv} \]

\[ \theta_5 \]

\[ i_{d, load, 5} \]
\[ i_{q, load, 5} \]
\[ m_{abc, 5} \]

\[ \theta_2 \]

\[ i_{d, inv, 5} \]
\[ i_{q, inv, 5} \]

\[ \text{LPF Filtering} \]
\[ \text{PI} \]
\[ \text{sat} \]

\[ d_{q} \]

\[ \text{DC voltage/active power and reactive power control} \]

\[ \text{Selective harmonics compensation based on synchronous reference frame for } 5^{th} \text{ and } n^{th} \text{ harmonics} \]

**Figure 3.** Selective harmonics compensation based on synchronous reference frame for 5\(^{th}\) and \(n^{th}\) harmonics

4. **Protective device construction**

During the research there was developed a protective controller against emergency modes for power networks with selective harmonics compensation, based on principles explained in chapters 2-3. The controller can be used together with existing power control systems or with own set of sensor and monitoring devices.

There are many existing prototypes [9,10]. Nevertheless, their application is limited only for conventional power networks. Implementation in DG-networks can be quite difficult. They do not have possibilities for selective cut out of non-important consumers, selective power compensation. Even reactive power compensation possibilities are built using conventional power theory that can be difficult to operate with in DG-networks [5]. As a result, important power grid characteristics can be lost and not taken into account during analysis. Hence, cascade outage can happen and develop into a catastrophic blackout and lead to big financial losses [11].

The topological scheme of the protective device is shown in figure 4. It operates in the following way. Initially an operator sets required power quality limits (deviations of frequency, inertia, THD etc.) in the Adjustable parameters module (1).

The protective controller communicates with one or more Smart low-level devices (11), which receive data about power networks and consumers. After collection, they are transferred into inner controller modules (2-10, 12-13).

Calculation results are delivered into Load control and cut out module (4) and Harmonics calculation module (12). The last one analyzes current and frequency parameters and gives data in the Control block for harmonics compensation (13), which is connected with Smart low-level device (11). Load control and cut out module (4) gives to the Smart low-level device instructions for selective consumers’ cut out or generators’ power increase in order to maintain power balance in the system.
5. Experimental prototype

In order to conduct a real experiment there was a created controller’s prototype, based on a single-board PC Raspberry PI 3 (see figure 5). The program code for protective algorithms was written in C++ language. The possible network’s model for controller implementation was developed in vision Network Analysis Program and is shown in figure 6. It was created in order to research control algorithms in DG power grids.

Figure 4. A topological scheme of the protective device

Figure 5. Developed controller’s prototype.

Testing stand included different 3-phase asynchronous motors with nominal power from 0.2 up to 5 kW. Figure 7 demonstrates controller’s operating technique. Distortions and emergency modes were created manually with the help of different non-linear loads and short-circuits between phases and ground.

Figure 6. Developed structure scheme for implementation of protective microcontroller against cascade outages into DG-networks.
Modelling and experimental results revealed that protective algorithms and controller’s prototype can save network and prevent total blackout due to selective disconnection of uncritical consumers and predictive control.

![Figure 7] Results of controller’s work

6. Conclusion
The growth of renewables sources changes power networks from conventional to DG-ones, makes scientists to explore new aspects of control theory in order to implement all renewables sources and deal with control problems. The large number of power converters that are implemented together with small generators requires development of new mechanisms and filters to isolate their distortions from the harmonics oscillations generated by non-linear loads.

Development of the controller’s prototype and its combinations with the active power filter allows one to predict and prevent cascade outages in DG networks due to effective compensation of harmonic currents and predictive control of all consumers. Testing results in the laboratory revealed big potential of this technique.

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