Modelling and analysis of functional modes of active compensators in distributed generation systems

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Abstract. The modelling and analysis of functional modes of active compensators in conditions of distributed generation are presented in the paper. The functions of uninterruptable power supply, harmonic compensation, power factor correction by means of the shunt active compensator with the output passive filter and the common direct current link with the load power converter are detected during modelling. The dependences, which help to properly choose the structure and main parameters of the active compensator for implementation of the mentioned functions, are obtained during modelling. According to the modelling results the structure of the shunt active compensator is proposed and proved for conditions of distributed generation and combined power supply systems.

1. Introduction
It is generally agreed today that the technical solutions for rising of power quality and electromagnetical compatibility are the key part of the whole necessary measures, which are intended for energy saving in industrial electrical networks [1]. Among the mentioned solutions the active compensators play an important role.

Nowadays in the modern industrial conditions the active compensators and converters are widely used both in centralized and distributed power supply systems. In case of conventional centralized power supply systems such converters are presented as a part of non-linear load. In case of distributed power supply systems such converters are the part of non-linear load and electrical installations of alternative sources and renewables [2].

Also these active compensators and converters are the basis of different correction devices, which are intended for improvement of power quality and electromagnetic compatibility, power factor correction, source and load asymmetry correction, voltage generation with the required level and frequency. These functions can be implemented separately or mutually, depending on the network configuration, source and load type [3]. Besides the mentioned functions may be realized separately by different devices and technical solutions as series and shunt active filters, hybrid filters, static reactive power compensators (STATCOM), dynamic voltage restorers (DVR), unified power flow controllers (UPFC) and others. From the technical and economical point of view it is reasonable to combine maximum functions in one active converter or compensator [4] with minimal structural changes.

That is why the problem of structural and parametric synthesis of active compensators is quite actual for improvement of power quality and electromagnetical compatibility especially in the distributed and combined power supply systems [5].
2. Active compensator’s types and features

The first thing that needs to be said is that all existing active compensators are implemented on the basis of voltage (VSI) or current source inverters (CSI) with input and output drossels or passive filters of the certain configuration.

The active compensators of series type are based on the CSI and are intended for correction of voltage drops, deviations, unbalance and distortion [5, 6]. In most cases they are connected to a network through the special transformer, which rated power is determined firstly by value and duration of the voltage drop and nominal load current. The algorithm of function of the series active compensator is frequently realized on the basis of the Fortescue transformations with determination of direct component of reference network voltage [5, 6].

The active compensators of shunt type are based on the VSI and are intended for correction of load current unbalance and distortion [5, 7]. They are also can be a part of power factor correction systems [5, 7]. The algorithm of function of the shunt active compensator is frequently realized on the basis of the Clark-Park phase transformations with determination of direct component of reference load current [7]. Nowadays there is a great amount of the different control algorithms which are developed and proved for the shunt active compensators [5] in the certain conditions, according to the results of the numerous researches. Among them it is reasonable to indicate the following main types: the algorithms, based on the \(abc-\alpha\beta\) phase transformations, the algorithms, based on the \(abc-dq\) phase transformations, the algorithms, based on the \(p-q\) theory, the algorithms, based on the fast and discrete Furier transformations, the fuzzy logic methods [7]. The general classification of the all plenty algorithms for control of the shunt active compensators should be made according to the mentioned main types.

The common feature of control systems of shunt and series active compensators is the usage of the phase locked loop (PLL) system for phase synchronization of reference and real signals. Also it is reasonable to use the relay regulators of current with variable hysteresis width [5, 8] for generation of control pulses for power elements of series or shunt active compensator according to the modeling results [5, 8]. Such solution helps to increase the dynamic response of compensator, decrease the thermal losses in power elements and provides the flexible mode of correction of harmonic distortion [8].

The all mentioned features should be taken into account when developing the rational and effective structure and the control algorithm of active compensators in the certain working modes of electric networks, sources and loads [9].

In this paper the modeling object is presented by the shunt active compensator with the control system on the basis of \(abc-\alpha\beta\) phase transformations, with the output passive filter and the common direct current (DC) link with the power converter of the non-linear load in conditions of the distributed generation from diesel engine.

3. The structure of the model of active compensator

A structure of electrical network with distributed generation with shunt active compensator, which has the common DC link with the power frequency converter of the non-linear load, is presented in Figure 1. The simulation model was developed in Matlab Simulink software according to the structure, which is presented in Figure 1.
The main aims of mathematical modelling and computer simulation are the follows: the evaluation of the influence degree of hysteresis width variation of the relay regulators on the efficiency level of harmonic elimination by the shunt active compensator, the determination of parameters and characteristics of the passive filter, installed on the output of the compensator, which allows one to improve the efficiency of harmonic elimination by the shunt active compensator in conditions of the large internal impedance of the distributed generation source [10], the analysis of the possibility of the shunt active compensator to realize the function of uninterruptable power supply during short-time faults in the network to ensure the required level of working stability of technological equipment’s motors, the evaluation of power factor correction by means of the active compensator [11, 12].

4. The modelling results

A spectral content of network voltage and current in cases of disconnected and connected shunt active compensator is presented in Figure 2a, b, respectively.

The dependences of the voltage and current total harmonic distortion factors $k_U$ and $k_I$ from the hysteresis width of relay regulators $H$ are presented in Figure 3a. A waveform of DC link voltage $U_{dc}$ in case of three-phase fault on the input of rectifier of frequency converter (see Figure 1) when the circuit breaker $QF$ is switched off due to fault in time 1.95 s after modelling start is presented in Figure 3b.
The modelling results, presented in Figure 2, show the ability of the shunt active compensator to eliminate voltage and current harmonics with the required level of efficiency. It is a well-known fact, but the usage of common DC link both for compensator and converter of non-linear load gives an opportunity to apply the shunt active compensator as an uninterruptable power supply [5, 13] in case of fault in network, as it can be seen in Figure 3b. One should note here that the duration of transient of DC link voltage is more than 0.25 s, which is not acceptable for some induction motors such as the submersible induction motors of centrifugal pumps of the oil extraction installations [5]. For such motors the permissible duration of voltage drops and interruptions, which guarantees the stable functioning of installation, must not exceed 0.15 s [5] according to the results of theoretical and experimental research. Doubtless that the control algorithm of the shunt active compensator should be modified and improved in part of the operation speed of charging and discharging modes of the DC link capacitor [14]. The dependences, presented in Figure 3a, may be used for adjustment of hysteresis width of the relay regulators of the shunt active compensator for the purposes of optimization of the thermal losses of compensator’s power elements when only the partial compensation of voltage and current harmonics is required [8]. Besides the variable hysteresis width of the relay regulators allows one to maintain a variable carrier frequency of pulse width modulation (PWM) of compensator’s VSI (see Figure 1) what also helps to optimize the thermal losses in VSI. It is clear from these studies [8] that the raising of the PWM carrier frequency leads to decreasing of the thermal losses of IGBT elements of VSI.

The generalized amplitude-frequency characteristic of the passive filter, installed on the output of the shunt active compensator, was obtained during modelling. This characteristic is presented in Figure 4.

![Figure 3](image1.png)

**Figure 3.** a – The dependences of the voltage and current total harmonic distortion factors from hysteresis width of relay regulators; b – A waveform of DC link voltage in case of three-phase fault.

![Figure 4](image2.png)

**Figure 4.** The generalized amplitude-frequency characteristic of the passive filter, installed on the output of the shunt active compensator.

This characteristic was obtained for the set of the different configurations of the passive filter, which are presented in Figure 5.
The set of the different configurations of the passive filter, installed on the output of the shunt active compensator.

The output passive filter with the obtained amplitude-frequency characteristic allows one to improve significantly the efficiency of voltage and current harmonic elimination, with usage of the shunt active compensator in conditions of the distributed generation, when the internal impedance of source reaches a high value in comparison with such value for the centralized power supply system. The modelling and evaluation results of the efficiency of voltage and current harmonic elimination by the shunt active compensator with the output passive filter of different configuration according to Figure 5 are presented in Table 1. Here one can see the degree of decreasing of the voltage \( \Delta k_U \) and the current \( \Delta k_I \) total harmonic distortion factors and also the value of the power factor \( k_M \) in conditions of power supply transferring from the centralized source to the distributed one, when the value of the internal impedance of network raises more than 5-7 times. The results, presented in Table 1, show that the maximal efficiency of voltage and current harmonic elimination in case of distributed generation is demonstrated by the shunt active compensator with the output passive inductive-capacitive filter, which configuration is presented in Figure 5e.

### Table 1. The modelling and evaluation results of the efficiency of voltage and current harmonic elimination by the shunt active compensator with the output passive filter of different configuration

| Configuration of the output passive filter according to Figure 3 | a  | b  | c  | d  | e  | f  | g  | h  |
|---------------------------------------------------------------|----|----|----|----|----|----|----|----|
| \( \Delta k_U, \% \)                                           | 36.3 | 49.37 | 37.34 | 52.93 | 57.11 | 34.94 | 37.34 | 55.13 |
| \( \Delta k_I, \% \)                                           | 84  | 78.03 | 84  | 84.41 | 84.83 | 83.89 | 86.82 | 84.41 |
| \( k_M \)                                                      | 0.96 | 0.98 | 0.96 | 0.97 | 0.97 | 0.96 | 0.88 | 0.97 |

Hereby the modelling results prove the necessity of installation of the passive filter on the output of the shunt active compensator when elimination of voltage and current harmonics in case of the distributed generation. Also it must be noted that the efficiency level of current harmonic elimination is greater than the similar level for voltage. Besides the studied shunt active compensator demonstrates a satisfactory efficiency of increasing of power factor.

### 5. Conclusion

The actuality and necessity of complex application of the distributed generation technologies in industrial power supply systems are proved. Also the actuality of the problem of power quality improvement is shown both for centralized and distributed networks.

The key role of active compensators of different types as an effective technical solution for power quality improvement is indicated. Besides it is proved that such compensators should be considered as a part of the multifunctional systems, which are intended for correction of the several power quality indicators, synchronization of parallel working of the several distributed sources, uninterruptable power supply in case of faults in the network.

The mathematical model of the shunt active compensator with the common DC link with the nonlinear load converter and the output passive filter in conditions of the distributed generation is developed. The modelling results show an ability of the studied shunt active compensator to eliminate voltage and current harmonics with the required level of efficiency in case of the large internal impedance of source,
to ensure uninterruptable power supply mode in case of faults at the input of non-linear load. The optimal configuration of the passive filter, installed on the output of the shunt active compensator, is detected by the criterion of the maximal efficiency of voltage and current harmonic elimination in conditions of the distributed generation. The modelling results also show an ability to adjust a hysteresis width of the relay regulators of control system of the shunt active compensator according to the given requirements of harmonic elimination depth. Besides the modelling results prove the ability to increase the power factor by means of the shunt active compensator.

The subject of the future research in this area is a modification of control algorithm of the shunt active compensator for improvement of damping of voltage dips in case of faults in the network.

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