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VSIG –VARIABLE SPEED INTEGRATED GENERATOR SYSTEM FOR DISTRIBUTED GENERATION

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ABSTRACT
This paper presents the operation and the results of tests of the variable speed integrated generator and power electronic system VSIG in both autonomous and grid connected modes. The distorted AC grid voltage produces nonsinusoidal current of the converter output capacitor low pass filter. The control described in this paper compensates for the harmonic current and then the grid is fed by sinusoidal current. The variable speed generation system may be useful for distributed generation.

KEY WORDS
Power electronics, permanent magnet generator, variable speed generation, power flow control, distributed generation

1. Introduction

Distributed generation is a recent concept of power generation on the part of users. The distributed generation is dedicated to support the main electrical power system EPS, to improve quality delivered power. A generating set is required to be able to operate in two modes, namely: grid connected and stand alone. There are two topologies that can be developed for the distributed generation. The first topology is based on the application of classical wound rotor synchronous generator. The second one is related to the application of power electronic converters.
The technique of wound rotor synchronous generator (Fig.1) is well developed and dominant in world power generation systems.
The synchronous generator produces the AC voltage whose angular frequency ω_g strictly depends on the rotating mechanical speed n and the poles pars p of the synchronous generator.

$$\omega_g = 2\pi f_g = 2\pi\, n / (60\, p) = \omega_{mg} / p \qquad (1)$$

where f_g stands for AC voltage frequency and ω_{mg} refers to the mechanical angular speed of the generator rotor.

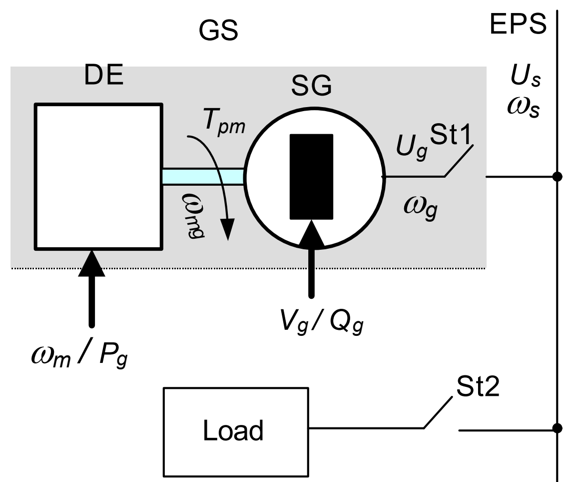

Fig. 1. Generation set with wound synchronous generator.

With regard to the island mode of operation (autonomous operation), in order to maintain the fixed reference frequency the prime mover DE speed has to be dealt with in a very precise manner, which is practically impossible. The deviation of the output voltage angular frequency $\Delta\omega_g$ is proportional to speed rate $\Delta\omega_{mg}$ and thus

$$\omega_{gr} + \Delta\omega_{gr} = 2\pi f_{gr} + \Delta f_g = 2\pi(n_r + \Delta n) / 60p = \\ = (\omega_{mgr} + \Delta\omega_{mg}) / p \qquad (2)$$

where ω_{gr}, f_{gr}, ω_{mgr} are rated values of the generator angular speed voltage, frequency and mechanical angular speed.

The sinusoidal emf. of the generator is the result of the linkage flux and the rotational motion of the generator. The linkage flux is controlled by the excitation current passing through the rotor winding.
High inductance exciter winding results in long time constant. Generators connected to a common bus result in higher power and stiffer electrical system.

Figure 2 shows a simplified vector diagram of the synchronous generator connected to the stiff power system in which the voltage is described by voltage vector U_s and angular frequency ω_s. The system is described with the use of rotating reference frame *d,jq* with angular speed ω_s of the voltage power system. The power transmitted from the generator to the grid is characterized by load angle δ_{sg}.
The generator current I_{gs} is displaced with respect to grid voltage by an angle φ_g. The main task of the generator operation is system stability. The stability is maintained when the load angle is kept below 90deg.
This is achieved by the control of mechanical speed with the assistance of the excitation circuit. The time constants of the speed control and excitation loop are much bigger than AC voltage periods. Therefore, even in spite of a relatively low load angle, grid perturbation frequently causes the generator disconnection.

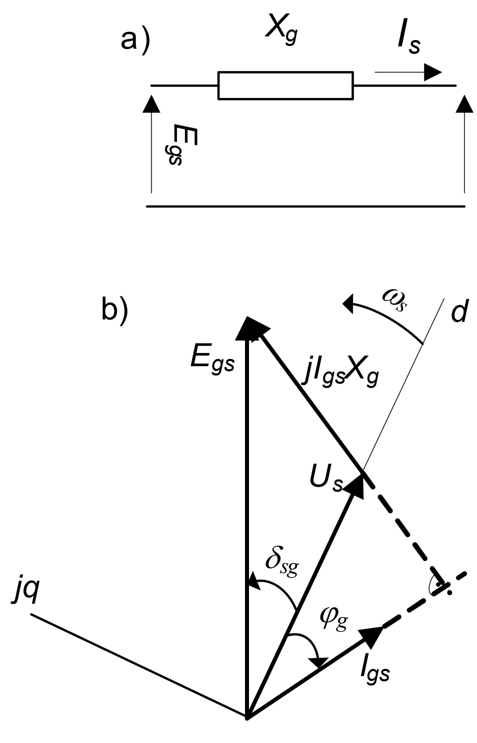

Fig. 2. Operation of wound synchronous generator connected to grid. a) equivalent diagram, b) simplified vector diagram oriented in rotating reference frame *d,jq*.

Moreover, nonlinear loads connected to grid (Fig. 3) produce harmonic currents that result in a voltage drop on the grid and across the generator. In case of the sinusoidal emf E_{gs} of the generator, the harmonic current makes the output voltage distorted.
Power electronic converters, which are widely applied to AC drives, may be used to provide power generation equipment. The issue of high frequency operation of power transistors or fully controlled thyristors introduces new concepts as far as the improvement of the generating system [6] is concerned.

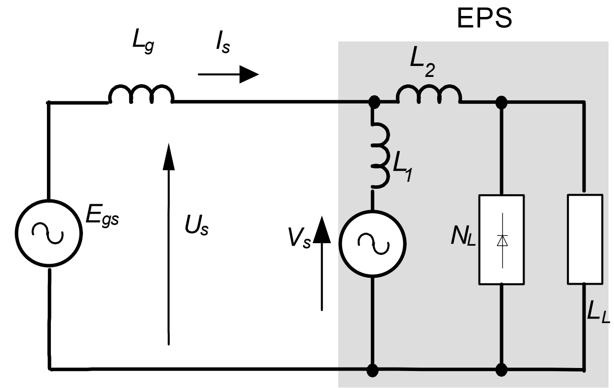

Fig. 3. Equivalent diagram of the wound synchronous generator connected to grid.

The power electronics output frequency controller is completely independent of the generator frequency and thus the generator may be designed with a different topology than the conventional generator.
The power electronic converter discussed in this paper operates in both autonomous and grid connected modes. The power electronics controller employs an adaptive technique to ensure suitable dynamics and power flow control.
The paper will present the results of tests 40kVA VSIG - variable speed integrated generator system.

2. Variable speed integrated generation system VSIG

The variable speed generation system (Fig.4.) consists of a driving engine DE, a generator G and a power electronic converter DPC. The power electronic converter DPC is supplied from the variable amplitude and frequency generator G and it produces fixed frequency and amplitude AC sinusoidal voltage. The system operates in a wide range of speeds, namely from 1000 to 3000 rpm. This speed range is based on torque response of the prime mover.

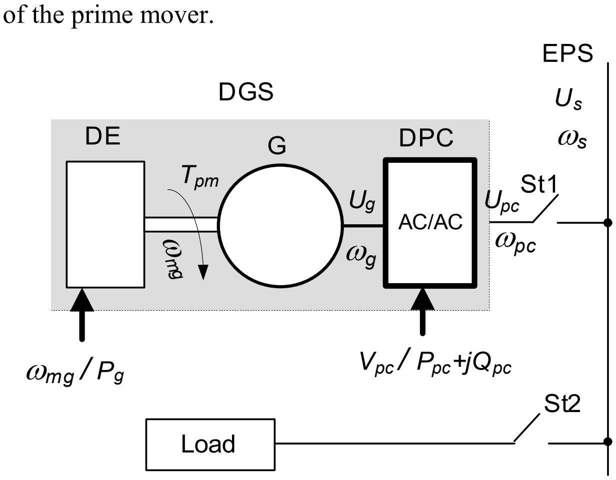

Fig. 4. Block diagram of the variable speed generation system.

The input and output voltage of the power electronics converter is shown in Fig. 5. In this case the system operates autonomously. The output 50Hz (that may be adjusted to 60Hz) is perfectly sinusoidal.
The generator employed is an axial flux permanent magnet generator [5], [6]. The PMG is light weight and short in length when compared to conventional machines. An example of 40kW permanent magnet generator is shown in Fig. 6 and 7. The permanent magnet generator is very short. Fig. 8 shows the generator mounted on the engine shaft.

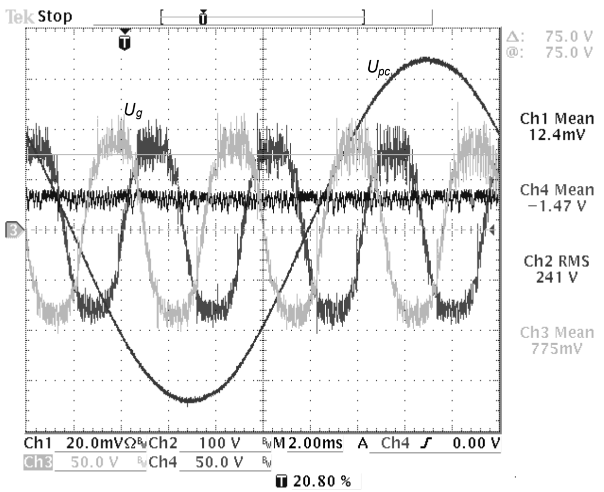

Fig.5. Generator and output AC voltage of the decoupled generating system. U_{pc} - output genset voltage, U_g - generator voltage

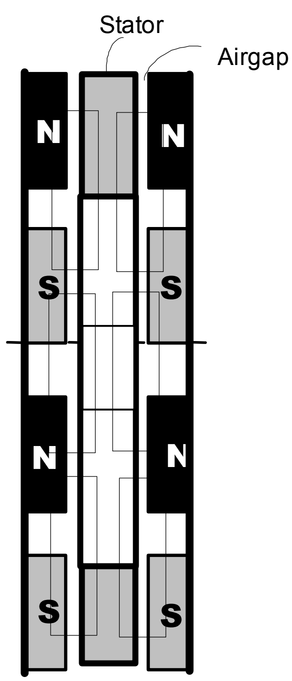

Fig. 6. Schematic cross section of the axial flux permanent magnet generator.

Examples of general topologies of power electronic converters are shown in Fig. 9 and 10. Both systems have intermediate DC link voltage. The three phase three wires system (Fig. 9) consists of DC voltage stabilizer DCg/DC and three phase bridge made from three legs IN-U, IN-V, IN-W. The DC link voltage stabilizer is used also as generator current controller.

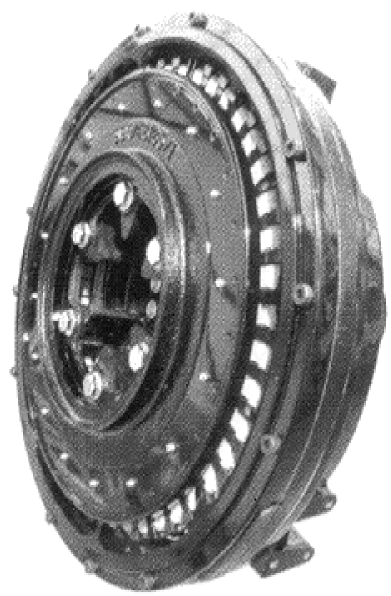

Fig. 7. Photograph of the Axial flux permanent magnet 40kW generator.

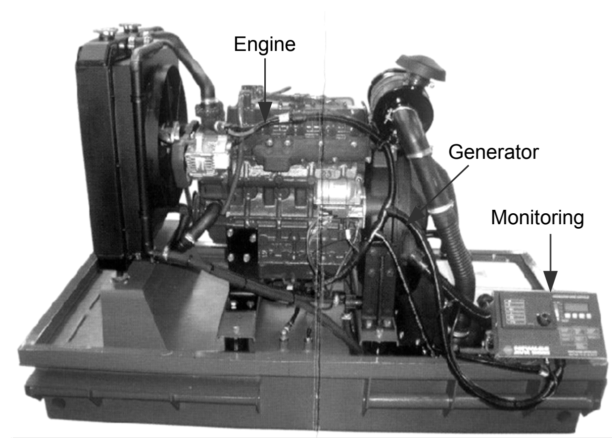

Fig. 8 Axial flux generator integrated to Diesel engine

The three phase four wires (Fig.10) are built using two DC link symmetrical voltages U_{dc1} and U_{dc2}. This enables us to produce three independent AC voltages.
A more detailed description of the three phase three wires system is shown in Fig. 11. The generator PMG produces AC variable frequency and amplitude voltage, whereas the rectifier Re changes this voltage to DC voltage. The DCg/DC step-up chopper stabilizes the DC link voltage U_{dc} on a level assuring the conversion of the DC voltage to demanded amplitude AC three phase voltage produced by the Co converter.

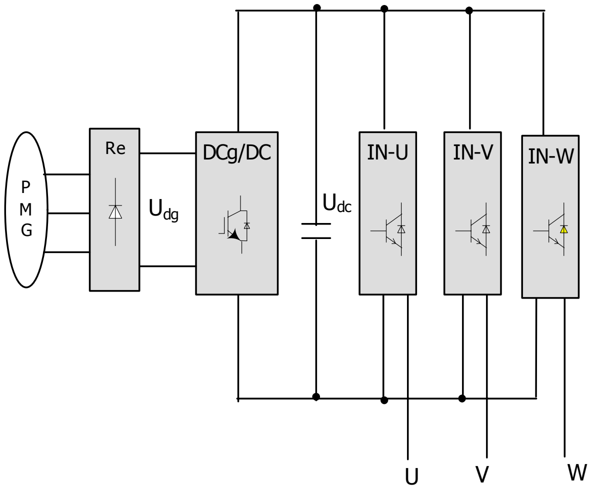

Fig. 9. Topology of the power electronic converter for three phase three wires system.

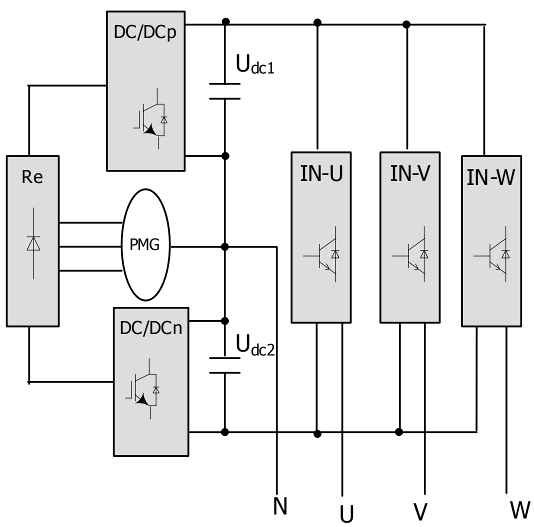

Fig. 10. Topology of the power electronic converter for three phase four wires system.

In order to achieve the sinusoidal output voltage, the power electronic converter should be equipped with LC low pass filter as shown in Fig. 11.

An equivalent diagram of the generating system connected to the grid is presented in Figure 12. When the generating system is connected to the grid, the output filter capacitor C_f may be charged by the grid stiff voltage.

For the sake of the adjustable speed operation, the system is equipped with speed regulator VSR as shown in Fig.13. The variable speed regulator VSR controls the engine speed and power delivered to the grid according to demanded active and reactive reference $P_r + Q_r$.

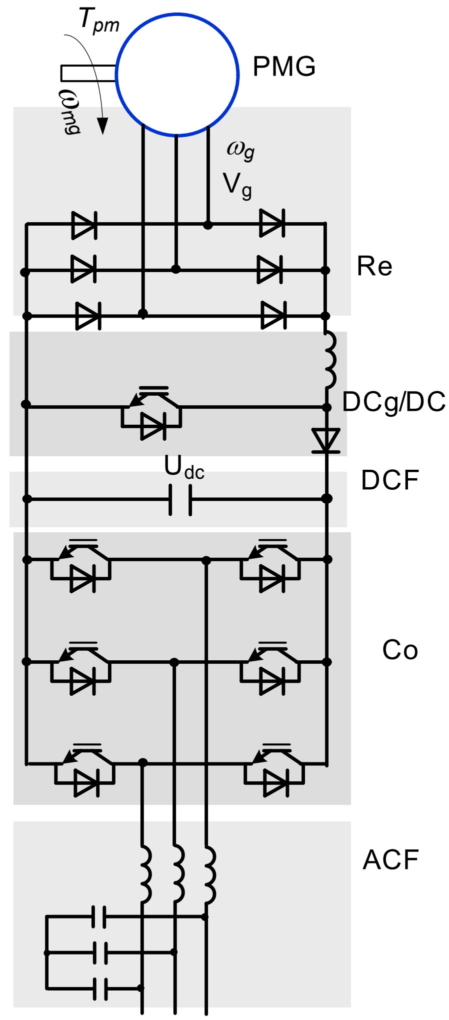

Fig. 11. Topology of the three phase three wires system.

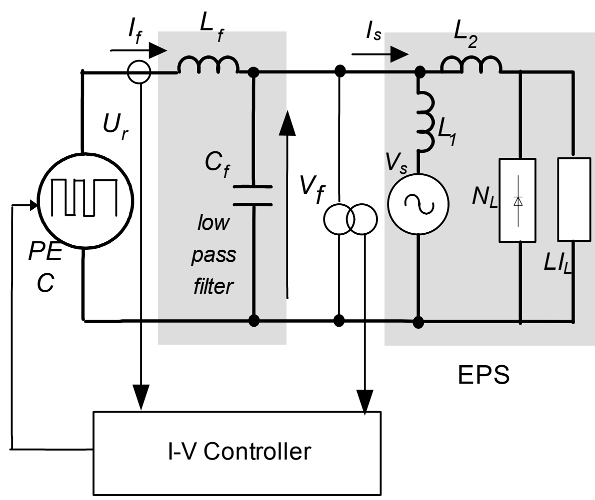

Fig. 12. Equivalent diagram of the variable speed generating system connected to the grid.

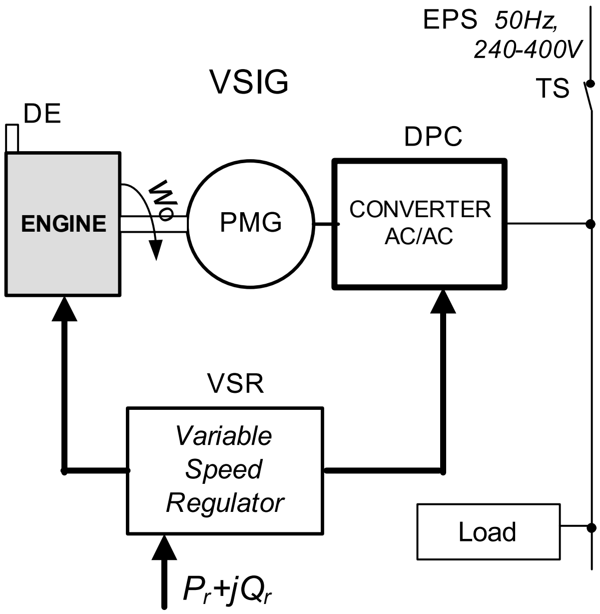

Fig. 13. Block diagram of the variable speed generation system connected to the grid.

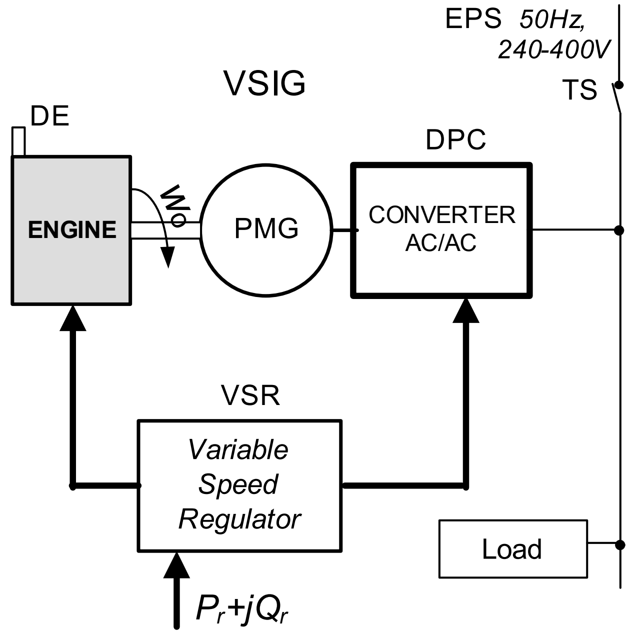

Fig. 14. Simplified vector diagram of the VSIG operation in case of grid connection.

3. Decoupled and compensated generation

The decoupled operation illustrated in Fig. 5 means that the generator voltage frequency and grid frequency are independent. In a system like that the generator has an additional degree of freedom. This situation is represented by the simplified vector diagram. The generator voltage vector is rotating with speed ω_g independently in direction and value regarding the grid vector.

When the converter is connected to the grid, the output filter capacitor C_f (Fig. 12) is charged by the additional current that,, theoretically, is out of control. Fig. 15 presents an oscillogram of the current delivered to grid by the variable speed generation system. The genset produces sinusoidal voltage but the grid voltage is distorted. This results in non-sinusoidal current (blue). The distortion of the current is produced by the distorted current of the filter capacitor C_f. The current delivered by the genset consists of the inductor current (green), which is sinusoidal, and the capacitor current. The sum of the sinusoidal choke controlled current and non-controlled capacitor current produces total distorted current. However, the developed method of control enables us to create sinusoidal grid current as proved by the oscillogram in Fig. 16.

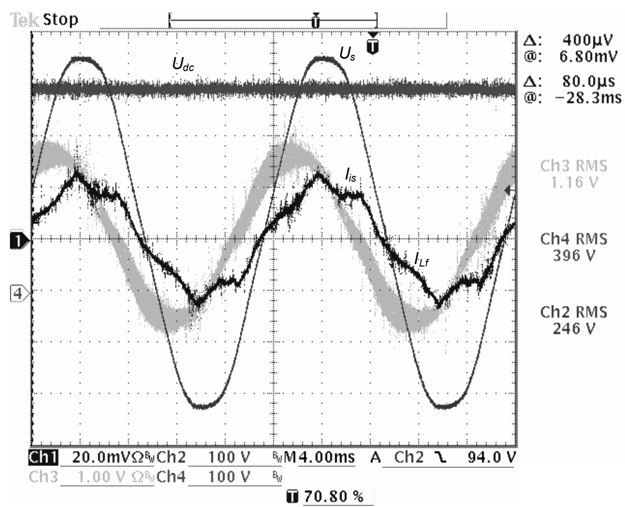

Fig. 15. Oscillogram of grid voltage U_s, filter inductor current I_{Lf} and grid current I_{is} – case of distorted AC voltage.

The compensation of harmonics is clearly visible. The system operates with power factor equal to one. As the amplitude of the current and its phase is under a precise control the load angle is also under control. This results in the enhanced stability of the generating system. Moreover, the frequency of the produced current does not depend on the load. The frequency and phase angle are controlled in accordance with the designed algorithm.

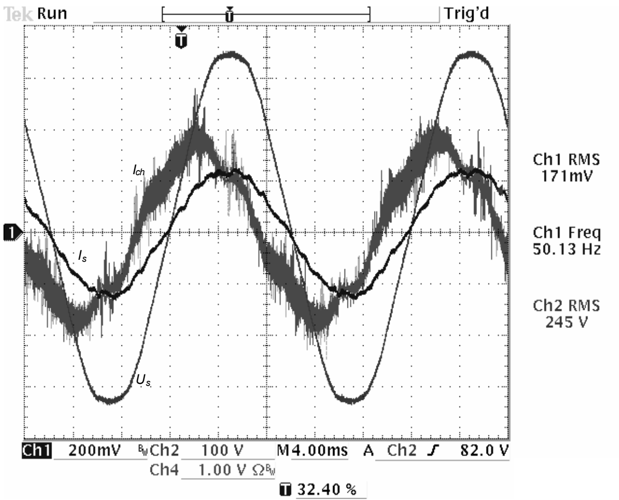

Fig.16. VSIG grid operation for a case of compensated controller, oscillograms: U_s – AC grid voltage, I_{ch} – inductor filter current, I_s – grid current.

4. Conclusion

- The variable speed generation system produces sinusoidal output voltage
- The decoupled generation provides an additional degree of freedom.
- The output filter capacitor is charged by nonsinusoidal current produced by nonsinusoidal grid voltage
- The developed method of harmonic compensation enables us to supply the grid by sinusoidal current

5. References

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