

# SYNCHROGENVERTER – PARALLEL CONNECTION OF SYNCHRONOUS GENERATOR AND POWER CONVERTER WITH ENERGY STORAGE\*

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**Abstract:** The paper describes a novel power generation topology wherein synchronous generator has a parallel connected power electronic converter. In this arrangement, the synchronous generator is only the source of active power and the power electronic converter is the source of reactive power. Such power distribution generated by the synchronous generator makes it possible to increase active power of by 25%, and operate with unity power factor. The power converter with energy storage system embedded can deliver additional active power in transient state to improve generator stability.

**Keywords:** *synchronous generator, power electronic converter, synchrogenverter, energy storage current control*

## 1. INTRODUCTION

Control of synchronous generator used nowadays is based on control of field current and driving torque. The torque is provided by external (gas turbine) or internal combustion engine (Diesel engine). Torque control is performed by mechanical equipment and depends on the type of applied engine and fuel. Control of synchronous generator is obtained by control of an excitation current. In the case of autonomous operation the excitation current is used to control generated output AC voltage whereas in the grid connection mode the excitation current controls reactive power. There are a number of topologies and controllers related to field control [1]–[3]. Overexcited synchronous machines were used as rotating source of reactive power (compensators) but recently they are replaced by power electronic converters (Statcom) [2]. Converter output currents and power are fully controllable. Therefore, the power electronic converters, producing reactive power, are used, for instance, as a source of reactive power in wind farms composed of induction generators which need additional reactive power to operate properly [3], [4]. In such to-

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pology induction generator delivers active power and is a consumer of reactive power. The recently developed adjustable speed generation system made from permanent magnet generator producing variable frequency voltage that is converted to fixed frequency and amplitude voltage performs with significant fuel saving. However, in such topology the output converter has to deliver active and reactive power [8], [9]. Moreover, the converter has to be over-dimensioned to cope with high short circuit current.

In the paper, a new integrated generation system is considered in which wound rotor synchronous generator WRSG is connected in parallel with power electronic converter PEC (Fig. 1). Such generation system, made as a connection of WRSG and PEC equipped with common control system (CCS), is called Synchrogenverter [11], [12]. A common control system CCS controls the WRSG active and reactive power, the DE driving torque and PEC active and reactive current respective to the reference signals  $R_{WRSG}$ . The PEC can change output current rapidly. So the synchrogenverter delivers proper amount of demanded load power even in transient states. Therefore the synchrogenverter output voltage and WRSG speed stability have better performance than WRSG alone. The WRSG and the PEC are connected in parallel so synchrogenverter output power, i.e., load power, is the sum of WRSG and the PEC power

$$S_{Lo} = S_{SGV} = P_{Lo} + jQ_{Lo} = (P_{GV} + P_{CV}) + j(Q_{GV} + Q_{CV}) \quad (1)$$

where  $S_{Lo}$ ,  $P_{Lo}$ ,  $Q_{Lo}$  – load volt-ampere power, active and reactive power,  $P_{GV}$ ,  $Q_{GV}$  – WRSG active and reactive power,  $P_{CV}$ ,  $Q_{CV}$  – PEC active and reactive power.

The synchrogenverter main principle of operation is that the WRSG delivers only active power but all demanded, by load, reactive power is delivered by the PEC.

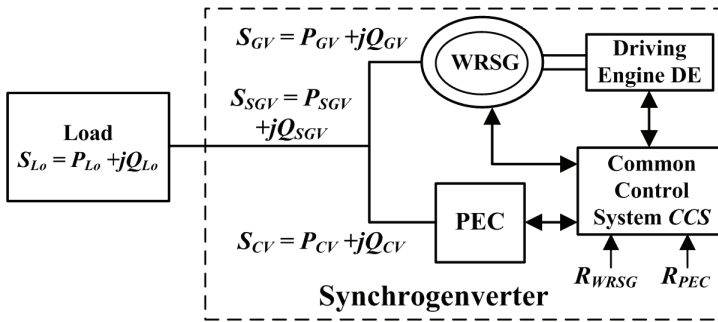


Fig. 1. General concept of the synchrogenverter

## 2. PRINCIPLES OF SYNCHROGENVERTER OPERATION

General topology of the synchrogenverter made from WRSG and PEC with common control system CCS, is presented in Fig. 2. However, there is considered a gen-

eral case where PEC includes additional energy storage system ESS. The PEC consists of an AC-DC converter TC, the energy storage DC-DC converter ESC and the energy storage system ESS. The CCS controls speed and driving torque of the engine by measurement and feedback signals  $CS_{DE}$ . The WRSg field current and output voltage is controlled by  $CS_{GV}$  signals from CCS.

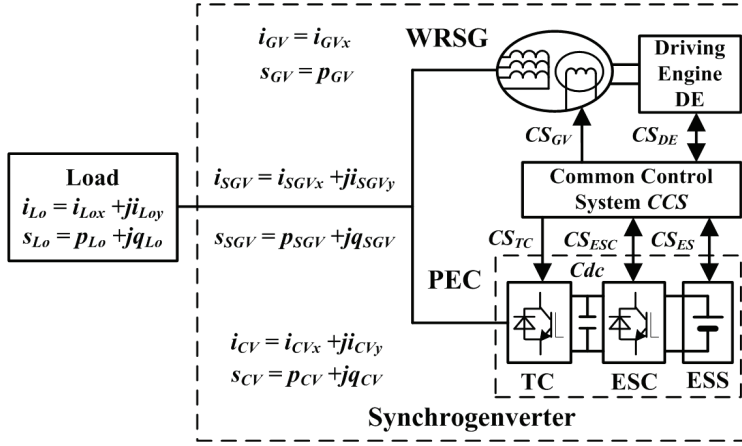


Fig. 2. Block diagram of the synchronverter

Energy storage voltage and current are controlled by signals  $CS_{ES}$  and by ESC converter controlled by  $CS_{ESC}$  signals. Output currents of PEC and DC-link capacitor  $C_{dc}$  voltage are controlled by  $CS_{TC}$  signals.

In the case of Fig. 2, PEC can deliver active  $P_{CV}$  and reactive power  $Q_{CV}$ , therefore its volt-ampere power equals

$$S_{CV} = P_{CV} + jQ_{CV}. \quad (2)$$

The general principle of synchronverter is that WRSg is generating only active power  $P_{GV}$ , zero reactive power  $Q_{GV} = 0$ ,

$$S_{GV} = P_{GV}. \quad (3)$$

Therefore, the load volt-ampere power delivered to the load

$$S_{Lo} = S_{SGV} = (P_{GV} + P_{CV}) + jQ_{CV}. \quad (4)$$

The control of synchronverter is based on voltage oriented control. The control system is in the rotating  $x$ - $y$  frame where  $x$  axis is rotating respectively to the WRSg output voltage vector  $v_{GV} = v_{GVx}$ . In such orientation instantaneous active power can be controlled by the  $x$  current component (active current) and instantaneous reactive power can be controlled by  $y$  current component (reactive current).

In the rotating  $x$ - $y$  frame WRSg current

$$\mathbf{i}_{GV} = i_{GVx} + j i_{GVy} \quad (5)$$

and PEC current

$$\mathbf{i}_{CV} = i_{CVx} + j i_{CVy}, \quad (6)$$

so the load active current

$$i_{Lox} = i_{GVx} + i_{CVx} \quad (7)$$

and load reactive current

$$i_{Loy} = i_{GVy} + i_{CVy}. \quad (8)$$

Taking into consideration equations (4) and (8), the load reactive current

$$i_{Loy} = i_{CVy}. \quad (9)$$

Current distribution between WRSg and PEC is maintained by CCS control, so the synchrogenverter output current

$$\mathbf{i}_{Lo} = \mathbf{i}_{SGV} = (i_{GVx} + i_{CVx}) + j i_{CVy}. \quad (10)$$

This state of the synchrogenverter operation is presented by vector diagram shown in Fig. 3a.

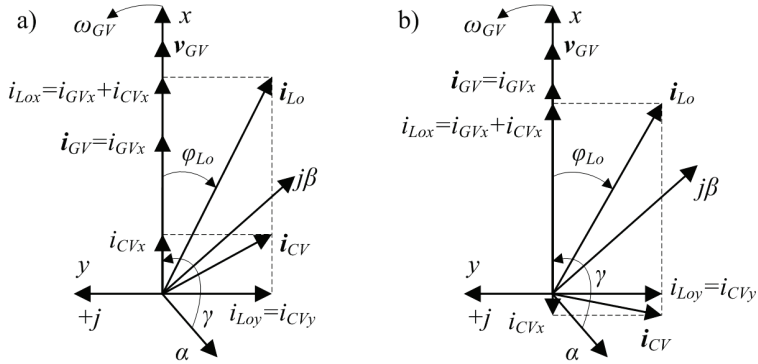


Fig. 3. Steady state of the synchrogenverter operation: (a) case of PEC delivery active and reactive power (according to topology shown in Fig. 2), (b) case of PEC delivery only reactive power (according to topology shown in Fig. 4)

A typical rating power factor of synchronous generator is  $\cos(\varphi_{Gn}) = 0.8$ . Therefore WRSg is producing only 80% of its rated power as active power, and the rest of power is reactive power

$$P_{GVn} = S_{GVn} \cos(\varphi_{Gn}) = 0.8S_{GVn}. \quad (11)$$

In synchrogenverter WRSG does not generate any reactive power so it can generate 100% of its rated power as active power, it operates with unity power factor  $\cos(\varphi_G) = 1$

$$P_{GV} = S_{GVn} \cos(\varphi_G) = 1S_{GVn}. \quad (12)$$

So, WRSG generates 25% more active power to the load with the same rated current but with  $\cos(\varphi_G) = 1$ . Generating inductive reactive power in synchronous generator requires increased field current. In synchrogenverter, WRSG does not generate any reactive power so it has less field current. Field winding current is DC and power losses depend on square of field current so in synchrogenverter rotor losses are significantly reduced.

PEC with energy storage can deliver active power to the load. The value of the active power and time of the active power delivery depend on the ES rating and capacity. Active power is delivered from energy storage ESS through ESC and TC converter and is controlled by CCS. Additional active power can be delivered during peak load or fast changing load. During low load or when load decrease ESS is charging, and during increase load ESS is discharging. In recent years there is an intensive development of energy storage [6], [7], [10]. Control of PEC output active and reactive current is practically instant, which can result in takeover of the load change by PEC and not by WRSG. Therefore, the synchrogenverter output power is of high quality and any oscillations are damped.

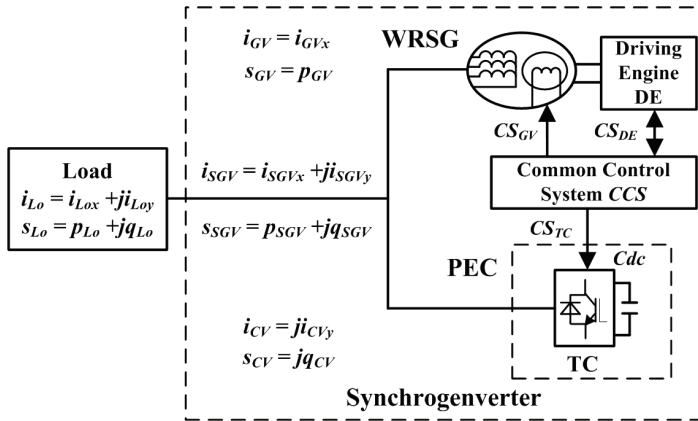


Fig. 4. The synchrogenverter topology with converter providing only reactive component

Modification of synchrogenverter topology is that PEC is only the TC converter without energy storage (Fig. 4). In this topology PEC can only deliver reactive power to the load. PEC has non zero active current to cover its losses, but compared to the WRSG active current it is insignificant  $i_{CVx} \ll i_{GVx}$  and can be neglected. So, PEC current in the case of topology from Fig. 4

$$\mathbf{i}_{CV} = j\mathbf{i}_{CVy} \quad (14)$$

and load current according (10)

$$\mathbf{i}_{Lo} = \mathbf{i}_{SGV} = i_{GVx} + j\mathbf{i}_{CVy}. \quad (15)$$

When PEC is not equipped with energy storage WRSG generates only active current and can generate 25% more active current (according to synchronous generator operating alone). The vector diagram for topology from Fig. 4 is presented in Fig. 3b.

## 2. PRINCIPLES OF SYNCHROGENVERTER OPERATION

The synchrogenverter topology and control system are shown in Fig. 5. Synchrogenverter presented in Fig. 5 responds to the topology presented in Fig. 2.

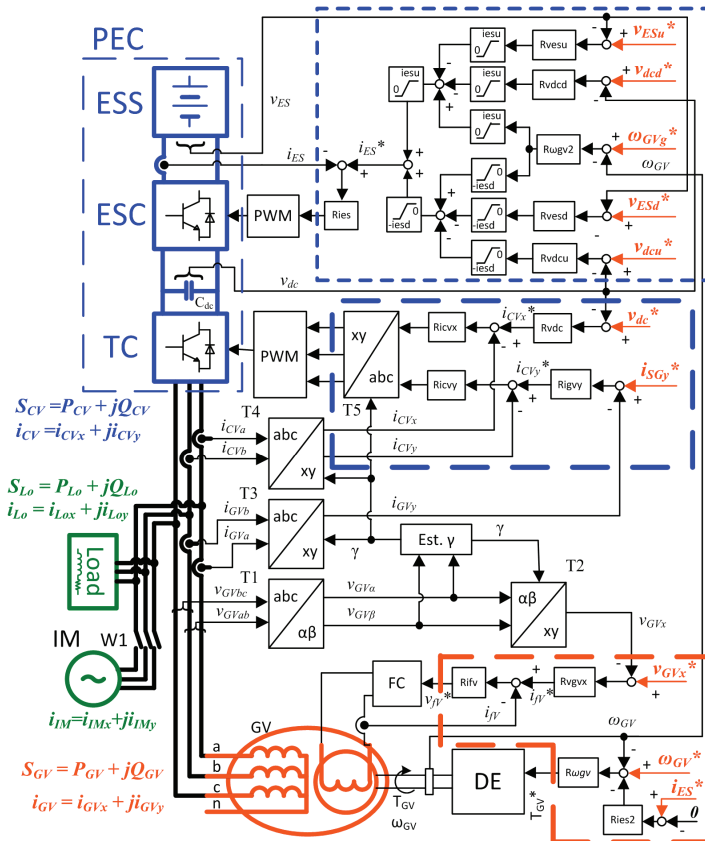


Fig. 5. Control concept of the synchrogenverter equipped with energy storage and converter as a source of active and reactive power

WRSG speed is controlled by  $R\omega_{gv}$  controller according reference value  $\omega_{GV}^*$ . The output signal of speed controller  $R\omega_{gv}$  is reference value of driving torque of DE. Speed difference is modified by energy storage controller RIES2 based on reference value of energy storage current  $i_{ES}^*$ . When ESS is discharging WRSG active power load is lower than load demand and DE driving torque should increase to take over active power. DE should decrease its driving torque when ESS is charging. RIES2 provide control of active power flow between WRSG and ESS in both cases when ESS is charging and discharging. Reactive current of PEC ensures zero reactive current of WRSG by WRSG reactive current controller RIGVY and PEC reactive current controller RICVY. Active current of PEC controls voltage of DC-link capacitor  $C_{dc}$ , and indirectly controls active power flow from ESS to the load. WRSG speed controller  $R\omega_{gv2}$  provides reference signal of ESS current  $i_{ES}^*$ . Reference value of ESS current can be zeroed by DC-link voltage controller RVDcd or RVDcu, or by the ESS voltage controller RVESd or RVESu. DC-link voltage controllers and ESS voltage controllers ensure these voltages maintain inside predetermined limits during charging or discharging of the ESS.

### 3. SIMULATION RESULTS

Computer simulation of synchrogenverter in autonomous operation is presented in Fig. 6. The synchrogenverter being tested was composed of WRSG, PEC and ESS, all rated in Table A1 (Appendix).

Figure 6 presents a synchrogenverter response to start of the 40 kW induction motor IM (rating in Table 1), initial load of synchrogenverter is 0.2 SGVN with  $\cos(\varphi_{Load}) = 0.8$ . Nominal active current of IM  $i_{IMx}$  is about 90 A. IM active current  $i_{IMx}$  during start is more than 200 A (Fig. 6a) so it is about 2 times greater than nominal current. IM reactive current  $i_{IMy}$  during start is about 400 A (Fig. 6a) which compared to the nominal IM reactive current is about 5 times greater. At the beginning of IM start WRSG active current  $i_{GVx}$  rises to cover IM demand. When WRSG active current rises its speed (Fig. 6c) drops and ES controller delivers active power to the IM (negative current of ESS, Fig. 6d). TC active current rises so WRGS active current drops (Fig. 6b) and speed is stabilized at referenced level. For comparison, a response of the synchronous generator operating alone is presented in Fig. 6c (blue line). Speed of WRSG in classical operation changes about 5% where in synchrogenverter speed changes about 1%.

WRSG principle of operation is that WRSG does not generate any reactive power in steady state. In the case of 50 kVA IM start reactive current of IM is greater than CV reference current and WRSG generates nonzero reactive current (Fig. 6f). In steady state WRSG does not generate any reactive current.

Output voltage of WRSG operating alone drops more than 20% while in synchrogenverter output voltage drops about 5% (Fig. 6g). WRSG reactive power in synchrogenverter is close to zero so its field current is lower than in classical operation. Power

losses in field winding depend on square of field current so in synchrogenverter power losses in field current are lower than in WRSG operating alone (Fig. 6h).

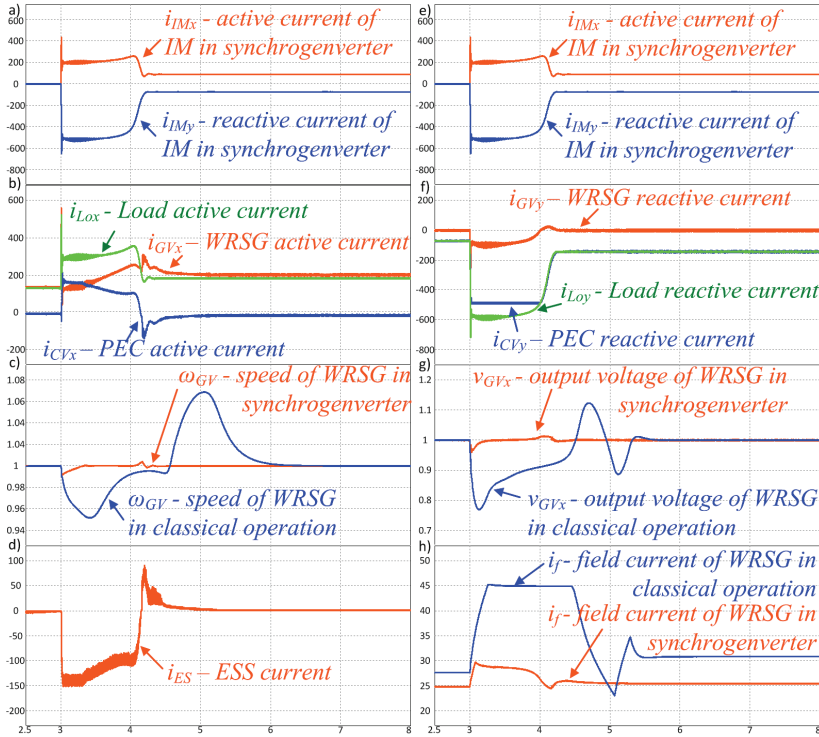


Fig. 6. Response of the synchrogenverter:

(a–d) case of start of 40 kW induction motor, (a) induction motor active component  $i_{IMx}$ , and reactive component  $i_{IMy}$ , (b)  $i_{Lox}$  – load current active component,  $i_{GVx}$  – synchronous generator active component,  $i_{CVx}$  – converter active component, (c)  $\omega_{GV}$  – (red) speed of the generator in the synchrogenverter,  $\omega_{GV}$  – (blue) speed of synchronous generator in classical operation, (d)  $i_{ES}$  actual current of the energy storage; respond of the synchrogenverter; (e–h) case of start of 40 kW induction motor, (e) induction motor active component  $i_{IMx}$ , and reactive component  $i_{IMy}$ , (f)  $i_{Loy}$  – load current reactive component,  $i_{GVy}$  – synchronous generator reactive component,  $i_{CVy}$  – converter reactive component, (g)  $v_{GVx}$  – (red) output voltage for the case of synchrogenverter operation,  $v_{GVx}$  – (blue) output voltage of synchronous generator classical operation, (h)  $i_f$  – (red) synchronous generator excitation current in case of synchrogenverter operation,  $i_f$  – (blue) synchronous generator excitation current in case of classical operation

#### 4. CONCLUSIONS

The paper presents novel topology and control of the generation system called synchrogenverter. The synchrogenverter consists of wound rotor synchronous gen-



erator operating as voltage source and parallel connected power electronic converter operating as current controlled voltage converter.

The synchrogenverter concept is based on control providing zero reactive current component of the synchronous generator. Thus by allocation of reactive power source from the synchronous generator to external converter provides increase of the synchronous generator productivity of active power about 25%. Therefore, the total synchrogenverter volt-ampere power is 125% of the synchronous generator operating alone. Moreover, fast operating power electronic converter delivers instantly reactive (and optional active power), which reduces significantly transient states and improves system stability.

## APPENDIX

Table A1. Data of the synchronous generator WRSG, induction motor IM, battery energy storage system ESS and TC power converter

Synchronous generator		Induction motor		Energy storage system		Power converter	
$S_{GVn}$	300 kVA	$S_{IMn}$	50 kVA	$P_{ES}$	100 kW	$S_{CVn}$	206 kVA
$P_{GVn}$	240 kW	$P_{IMn}$	40 kW	$V_{ES}$	700 V	$P_{CVn}$	100 kW
$Q_{GVn}$	180 kVar	$Q_{IMn}$	30 kVar	$I_{ES}$	145 A	$Q_{CVn}$	180 kVA
$U_{GVn}$	400/230 V	$I_{IMn}$	113 A	Capacity	1 kWh		
$I_{GVn}$	435 A	$I_{IMr}/I_{IMn}$	6.5				
$X_{GV}$	6 m $\Omega$	$U_{\beta IMn}$	230 V				
$L_f$	2.8 mH	$\cos\phi_{IMn}$	0.8				
$R_f$	1.3 m $\Omega$	$n_{IMn}$	990 rpm				
$\cos\phi_{GVn}$	0.8						
$I_{\beta n}$	45 A						
$n_{GVn}$	1500 rpm						

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