Sensorless Operation of a PWM Rectifier for En-Gen Set as a Distributed Generation

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***Abstract*— In this paper an engine generator (en-gen) set is used as a distributed generation system. This paper presents the interface and control strategies for the en-gen set using a PWM rectifier without any ac reactors and voltage sensors. A scheme to estimate the generator's EMF voltage from the measurement of ac line currents, a method to get a synchronous angle from the estimated EMF voltages and techniques of obtaining the integrators' initial values in the estimator are proposed. The feasibility of the overall algorithms has been verified throughout experiments using a 35hp commercial en-gen set.**

I. Introduction

To handle ac line currents as dc values in a synchronous reference frame is a well-known technique for the control of a PWM rectifier. In a general power circuit using PWM boost rectifier, ac line reactor should be inserted between the power grid and the PWM rectifier to meet the THD regulation of line currents as shown in Fig.1 [1]. For the operation of a PWM rectifier, ac side current sensors and dc side voltage sensor are prerequisite not only for the feedback signals of the respective controllers but also for the protections of the overall system. Ac line voltage sensors are not essential but optional for obtaining the synchronous angle. Therefore researches to control the PWM rectifier without the ac side voltage sensors have been done [2-4] for the respect of reducing the system cost and increasing the system reliability. From the switching states of the rectifier in [2], an instantaneous power and a reactive power were calculated, similar to the direct torque control of the motor drives, and then line voltages were estimated using measured current and calculated powers. Dc side voltage and ac side voltage were estimated in [3], and a little bit complicated method was suggested where the output pole voltages according to each of the switching states of the rectifier should be known for obtaining the ac line and dc side voltages and briefly introduced the problem coming from initial values of states in the estimator. In [4], it regarded the power grid and the line inductances as an ac machine model and simply used the equations of the PWM rectifier, so that the source voltages were obtained by adding the output voltage of the current controller to the voltage drop at line inductance only by measuring line currents. It did not mention the problems such as an over-current in ac side and an over-voltage in dc bus side at the startup of the rectifier mainly caused by the slow convergence of estimator due to low gains and initial errors, and the problems can be solved by setting the proper initial values of states in the estimator. In this paper, the power grid is replaced by the distributed generator unlike the conventional system. The current controller in a synchronous reference frame is adopted, and by using its current feedback signals as input signals of the estimator, the source voltage estimator is simply designed on the software. The initial value problems at startup of the rectifier will be addressed.

Fig.2 shows a target system to control the power flows from the en-gen set to the utility grid. The system is set up to verify the interface method and control strategies for distributed generation system. In the target system, ac line reactors are not required since the inductances of the generator itself are large enough to suppress switching ripples due to the PWM rectifier. The system being compared with the conventional PWM rectifier, it should be noted that not EMF voltages of the generator but terminal voltages of the generator are only accessible to measure the voltages in the target system. However the shape of the terminal voltage shows a pulse width modulation pattern, because of the switching of the PWM rectifier. For the unity power factor operation of a PWM rectifier, not the angle of the terminal voltage but that of EMF voltages of the generator should be estimated since EMF

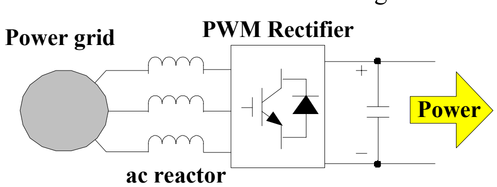

Fig.1 Conventional structure of a PWM rectifier

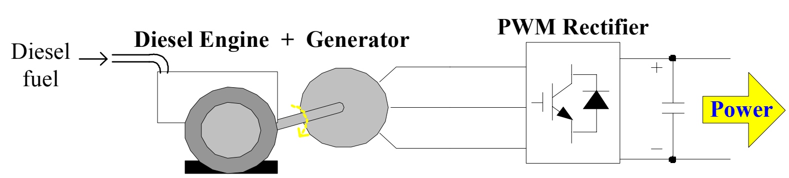

Fig. 2 Structure of the proposed en-gen set

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voltages of the generator in the target system are corresponding to the source voltage of power grid in the conventional system. The EMF voltages of the generator have a different characteristic from source voltages in power grid. The frequency and the magnitude of EMF voltages of the generator are not constant but varied according to load change. Additionally in this system shown in Fig.2, the frequency varies according to the engine speed and the EMF voltage according to both of the field current of generator and the engine speed.

II. EMF VOLTAGE ESTIMATION METHOD

Originally the frequency of the EMF voltage (ω_e) should contain dynamics of engine but the generator and a PWM rectifier are able to be electrically represented as a Fig.3 since the mechanical dynamics of the engine are much slower than that of the electric system and the time constant of field winding of the generator is quite large compared to the dynamics of the proposed control system. The EMF voltages of the generator can be assumed in stationary reference frame as (1),

$$\begin{aligned} E_a^{\ s} &= -E\sin\omega_e t \\ E_b^{\ s} &= -E\sin(\omega_e t - 2\pi/3) \\ E_c^{\ s} &= -E\sin(\omega_e t + 2\pi/3) \end{aligned} \;\Rightarrow\; \begin{aligned} E_d^{\ s} &= -E\sin\omega_e t \\ E_q^{\ s} &= E\cos\omega_e t \end{aligned} \quad (1)$$

The voltage equation of the PWM rectifier is expressed as (2),

$$\mathbf{E_{abc}}^{\mathbf{s}} = -\left(L_s\frac{d}{dt} + R_s\right)\mathbf{i_{abc}}^{\mathbf{s}} + \mathbf{V_{abc}}^{\mathbf{s}} \quad (2)$$

,where $\mathbf{E_{abc}}^{\mathbf{s}} = \left[E_a^{\ s} \quad E_b^{\ s} \quad E_c^{\ s}\right]^T$, $\mathbf{i_{abc}}^{\mathbf{s}} = \left[i_a^{\ s} \quad i_b^{\ s} \quad i_c^{\ s}\right]^T$ and $\mathbf{V_{abc}}^{\mathbf{s}} = \left[v_a^{\ s} \quad v_b^{\ s} \quad v_c^{\ s}\right]^T$. It can be rewritten as (3) in the d-q stationary reference frame.

$$\mathbf{E_{dq}}^{\mathbf{s}} = -L_s\frac{d\mathbf{i_{dq}}^{\mathbf{s}}}{dt} - R_s\mathbf{i_{dq}}^{\mathbf{s}} + \mathbf{V_{dq}}^{\mathbf{s}} \quad (3)$$

Using the rotational transformation ($\mathbf{e}^{-j\hat{\theta}_e}$) in (4), it can be transformed to (5) in an estimated synchronous reference frame, where $\hat{\theta}_e$ means the estimated synchronous angle of EMF voltages.

$$\mathbf{e}^{-j\hat{\theta}_e}\cdot\mathbf{E_{dq}}^{\mathbf{s}} = -L_s\cdot\mathbf{e}^{-j\hat{\theta}_e}\cdot\frac{d\mathbf{i_{dq}}^{\mathbf{s}}}{dt} - R_s\cdot\mathbf{e}^{-j\hat{\theta}_e}\cdot\mathbf{i_{dq}}^{\mathbf{s}} + \mathbf{e}^{-j\hat{\theta}_e}\cdot\mathbf{V_{dq}}^{\mathbf{s}} \quad (4)$$

$$\mathbf{E_{dq}}^{\hat{\mathbf{e}}} = -L_s\left(\frac{d\mathbf{i_{dq}}^{\hat{\mathbf{e}}}}{dt} + j\hat{\omega}_e\mathbf{i_{dq}}^{\hat{\mathbf{e}}}\right) - R_s\cdot\mathbf{i_{dq}}^{\hat{\mathbf{e}}} + \mathbf{V_{dq}}^{\hat{\mathbf{e}}} \quad (5)$$

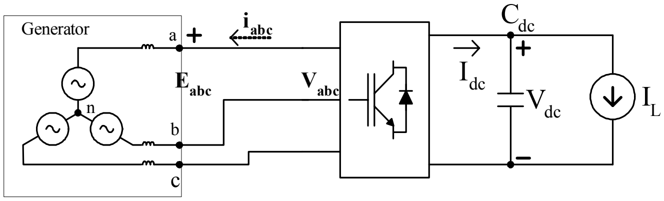

Fig. 3 Electric model of a en-gen set

The EMF voltages in the estimated synchronous reference frame ($\mathbf{E_{dq}}^{\hat{\mathbf{e}}}$) has the relationship with the real values ($\mathbf{E_{dq}}^{\mathbf{e}}$) as follows. The angle error can be derived from the arctangent function based on (7).

$$\mathbf{E_{dq}}^{\hat{\mathbf{e}}} = \mathbf{e}^{-j\hat{\theta}_e}\cdot\mathbf{E_{dq}}^{\mathbf{s}} = \mathbf{e}^{-j\hat{\theta}_e}\cdot\mathbf{e}^{j\theta_e}\mathbf{E_{dq}}^{\mathbf{e}} = \mathbf{e}^{j(\theta_e-\hat{\theta}_e)}\cdot\mathbf{E_{dq}}^{\mathbf{e}}$$

$$= \mathbf{e}^{j(\Delta\theta_e)}\cdot\mathbf{E_{dq}}^{\mathbf{e}} \quad (6)$$

$$\mathbf{E_{dq}}^{\hat{\mathbf{e}}} = \mathbf{e}^{j(\Delta\theta_e)}\cdot j\mathbf{E} \;\Leftrightarrow\; \begin{aligned} E_d^{\ \hat{e}} &= -\hat{E}\sin(\theta_e - \hat{\theta}_e) \\ E_q^{\ \hat{e}} &= \hat{E}\cos(\theta_e - \hat{\theta}_e) \end{aligned} \quad (7)$$

If the current controller designed in the estimated synchronous reference frame works well, EMF voltage estimator can be implemented by the outputs of the current controller ($\mathbf{V_{dq}}^{\hat{\mathbf{e}}}$) and the measured currents ($\mathbf{i_{dq}}^{\hat{\mathbf{e}}}$) as shown in Fig.4. By the phase locked loop (PLL) algorithm in a Fig.5, the synchronous angle can be estimated. Two PI regulators are used for obtaining the synchronous reference angle as shown in Fig.4-5. In these cases, the initial values of the integrators are critical to the stability of the overall system. It will be considered in next chapter.

III. STARTING PROBLEMS & OPERATING SEQUENCE IN EN-GEN SET WITH PWM RECTIFIER

At the starting of the en-gen set, governor of a diesel engine forces the generator to accelerate and to rotate around the rated speed (most of all industry products en-gen set operate around the rated speed, 50 Hz/60 Hz), and simultaneously dc bus voltage is initially charged up to the peak of the line to line voltage $\sqrt{3}E(=V_{\mathbf{dco}})$. The switching of PWM rectifier begins after the initial charge. If the dc capacitance of the dc bus (C_{dc}) is small, an initial error of a synchronous angle at the starting of current control (switching) may lead to boosting of the dc bus voltage. What is worse, it could reach an over-voltage trip level, since the PI gains of PLL are small for the robustness to disturbances.

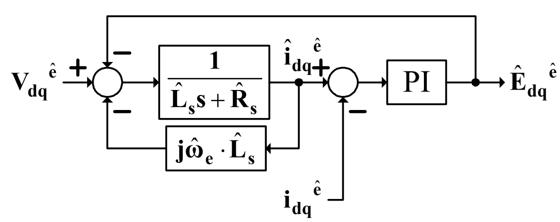

Fig. 4 EMF voltage estimator
in an estimated synchronous reference frame

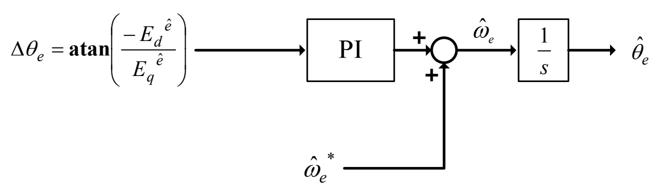

Fig. 5 Synchronous angle estimation using PLL

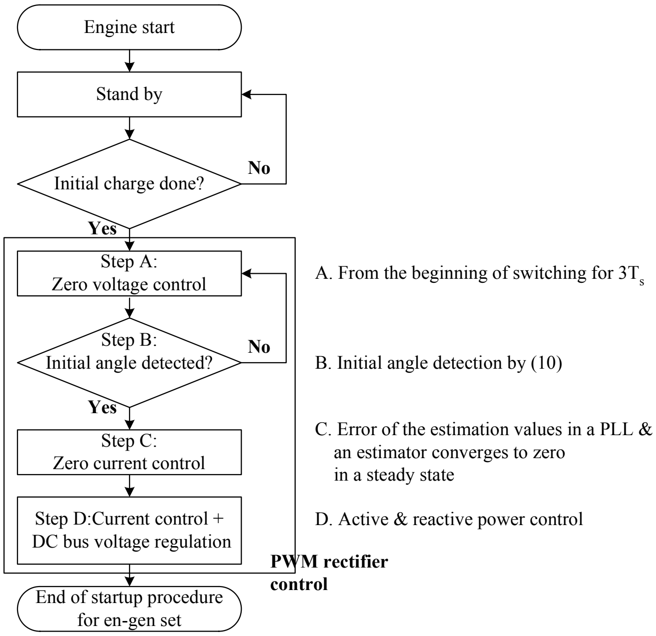

Fig. 6 startup procedure for an en-gen set

To improve the dynamics of the estimators with the low PI gains in Figs.4-5, the initial values of the integrators should be set as (8-9).

$$\hat{\mathbf{E}}_{\mathbf{dq}}{}^{\hat{e}}{}_{\mathbf{Initial}} \approx \mathbf{j}V_{\mathbf{dco}} / \sqrt{3} \tag{8}$$

$$\hat{\omega}_{e\mathbf{initial}} = 0,\ \omega_e^* = \omega_{rated} \text{ or } \hat{\omega}_{e\mathbf{initial}} = \omega_{rated},\ \omega_e^* = 0 \tag{9}$$

Additionally in order to get the initial value of the synchronous angle, the voltage references for the PWM rectifier are set to zero from the starting of the PWM switching for the first three sampling periods. The initial angle ($\hat{\theta}_{e\mathbf{Initial}}$) can be calculated by (10) from the measurement of ac line currents during these periods.

$$\mathbf{E}_{\mathbf{dq}}{}^{s} \approx -L_s \frac{d\mathbf{i}_{\mathbf{dq}}{}^{s}}{dt} + \mathbf{V}_{\mathbf{dq}}{}^{s} \Leftrightarrow \mathbf{E}_{\mathbf{dq}}{}^{s} \approx -L_s \frac{d\mathbf{i}_{\mathbf{dq}}{}^{s}}{dt} + 0 = -L_s \frac{\Delta\mathbf{i}_{\mathbf{dq}}{}^{s}}{\Delta\mathrm{T}}$$

$$\hat{\theta}_{e\mathbf{Initial}} = \mathrm{atan}\left(-\frac{E_d{}^s}{E_q{}^s}\right) = \mathrm{atan}\left(-\frac{\Delta i_d{}^s}{\Delta i_q{}^s}\right) \tag{10}$$

The sensorless operating sequence for the en-gen set is depicted as Fig.6. First of all engine starts, while the dc bus voltage is getting charged. The PWM rectifier starts to synthesize zero voltage for a short period, for obtaining the initial angle. Note that this duration for the zero voltage control at step B should be restricted short for the line currents not to reach the over-current trip level, even though the inductance of a generator is large enough to prevent the line currents from reaching the trip level for the short duration. The initial values in (8-10) should be set at the instant when it begins the zero current control at step C. By starting the zero current control, the output voltages of current controller are getting identical gradually with the EMF voltage of the generator. Finally the power flow control begins at step D. The overall control scheme for en-gen set is shown in Fig.7. It consists of an estimation part and two control parts, the estimation for a synchronous angle, the power flow control for a PWM rectifier, and the actuator control for both fuel of the engine and field current of the generator. In the prototype system, the actuator control is not the scope of this paper, but through the actuator control system, the en-gen set would be operated at various speeds dependent on the dc load condition, that is, at an optimum efficient operating point of the engine. In this paper the field current is controlled constant, and the speed of the diesel engine is not controlled precisely but it operated around the rated speed. In the future work, the actuator control system according to the engine map data might be augmented to the proposed control system.

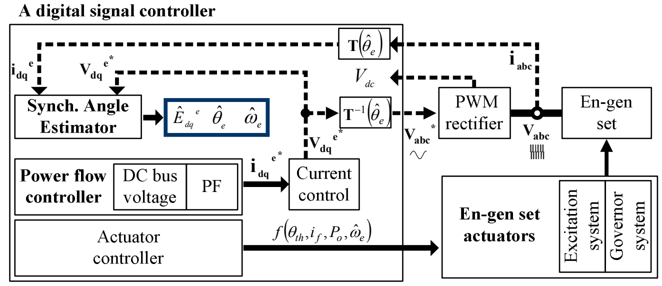

Fig. 7 Overall control strategies

IV. EXPERIMENTS RESULTS

Experiments have been performed using the 35Hp en-gen set and PWM rectifier system to verify the feasibility of the proposed sensorless algorithms. Table I shows the specification of the prototype en-gen set. The block diagram of the experimental setup is shown in Fig.8. PWM inverter acts as an electrical load interfaced with power grid. The output voltage of the current controller and an estimated d-axis EMF voltage in stationary reference frame are shown in Fig.9(a). In the case of no load condition, it is natural that both of them are exactly well synchronized with the estimated synchronous angle, since the impedance drop occurred at inductance of the generator is zero. In case of the loaded condition, note that the estimated d-axis EMF voltage is getting ahead of the output voltage of current controller by the angle difference in which it exactly matches the impedance drop($\omega \cdot L \cdot i_q{}^e$). It can be seen in Fig.9 (b) that dc bus voltage is well regulated with the unity power factor even in the step

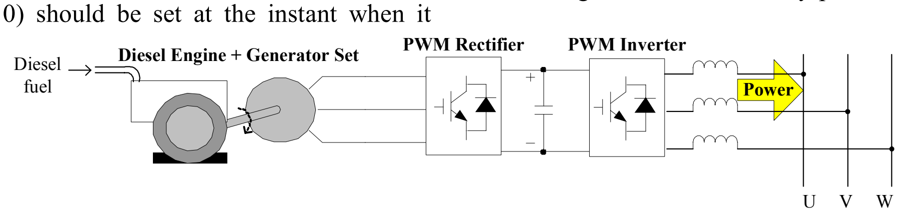

Fig. 8 Overall system for experiments

load change by the proposed sensorless algorithm.

TABLE I SPECIFICATION OF THE EN-GEN SET

Gen.	Frequency	60Hz
	Rated speed	60Hz(3600r/min)
	Phase wire	3-Phase 4-Wire
	Voltage	AC 200~480V
	No. of pole	2
	Bearing	Direct coupling with engine
Engine	Type	Vertical, water cooled, 4-cycle diesel
	Combustion system	Direct injection
	Continuous rated output	35hp
	No of cylinders	3
	Displacement	1496cc
	Fuel consumption	8.2 L/h

V. CONCLUSIONS

This paper presents a practical scheme to implement and to control the engine generator system with a PWM rectifier as a distributed generation. The current controller in a synchronous reference frame is adopted, and using its current feedback signals as input signals of estimator, the synchronous angle estimator is simply designed on the software without any additional hardware. The initial values of states/variables in estimator and PLL on the software at the startup of a PWM rectifier have been properly set for the fast convergence of the estimator and stability of the system. The feasibility of the proposed method has been verified by experiments.

ACKNOWLEDGEMENT

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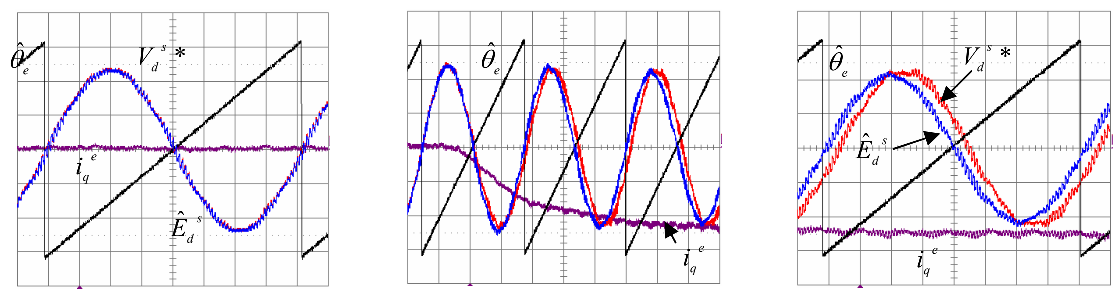
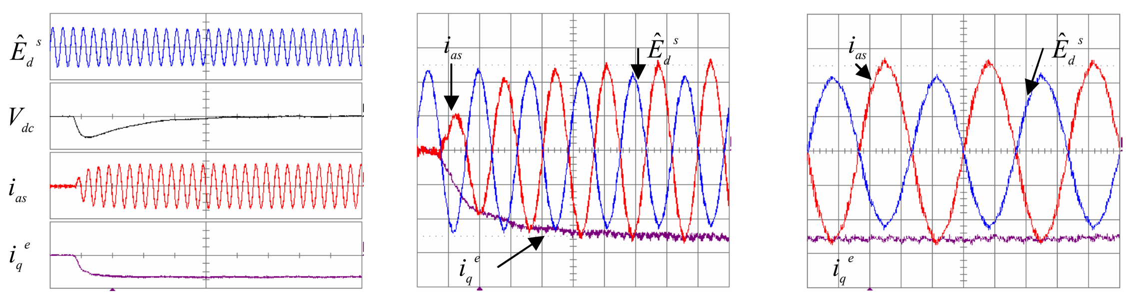


2msec/div — In no load condition | 5msec/div — In transient | 2msec/div — In 12*kW* load condition

(a) Estimation performance($\hat{\theta}_e$:1rad/div, $V_d^s*, \hat{E}_d^s$:125V/div, i_q^e :10A/div @ 700V$_{dc}$ regulation)



50msec/div | 10msec/div | 5msec/div

(b) Control performance($\hat{E}_d^s$:125V/div, i_q^e :10A/div V_{dc} :25V/div, mid 700V$_{dc}$)

Fig.9 Experimental results