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Asynchronous Generator Cooperation with Battery

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Abstract: - Low-power local networks with one generator can be stabilized by accumulator energy. Electrochemical battery can solve the problem of power ripples. Only slow balancing in longer period is necessary to keep the battery in charged stay. Battery voltage allows the use of cheap asynchronous generator in variable speed applications, where always converter must be used. Also in vehicle board-net supply asynchronous generator can be applied.

Key-Words: - Asynchronous generator, variable speed, harmonic current, controlled converter, model, battery

1 Introduction

Variable speed power generators are used in wind power plants and new economical mobile power sets, where the output power is speed proportional. The torque is approximately constant at Diesel or growing with speed in wind turbine drive. In low power applications Synchronous Generator with Permanent Magnet field (PMSG) is mostly used because of its best efficiency, no field control and no need of electrical energy for field exciting. Power electronics converter must always support it, to get constant frequency and voltage at the terminals Fig.1. Direct AC/AC converters are not used yet; therefore it is always 2-step conversion with DC constant voltage inter-circuit. In the local network the continuous energy delivery is protected by accumulator battery, parallel connected to DC circuit (Fig.1).

Cheap and robust Asynchronous Generator (AG) with capacitor excitation was applied in small power units with constant speed in last two decades. Its use for variable speed operation was few years ago unsuitable, because for each frequency it needs another value of parallel capacitor in autonomous run. Only switched converter techniques progress brings back the idea to use cheap, simple and robust AG in power generating at variable speed, namely if battery is to disposal for reactive power delivery during the start. Converter control for AG also can be simpler and cheaper than for SG, because synchronism is not strictly necessary.

The road vehicles are also equipped by battery, supplying the board net. Generators are supposed to deliver constant maximal power (load is limited) at wide speed range of modern engines. The field coil rotor SG is used nowadays supplied by brushes from electronic controller. Stator winding supplies battery (and all the net) via diode rectifier (DC output). Brush-less generator offers higher reliability and cage-rotor AG with integrated AC/DC inverter can best replace actual synchronous alternator with field controller and rectifier, with at least equal efficiency and higher reliability.

2 Asynchronous Generator Properties

Typical 50Hz AG is connected in stabile wide-area net (which keeps its voltage and frequency) and is driven by speed slightly over the synchronous speed:

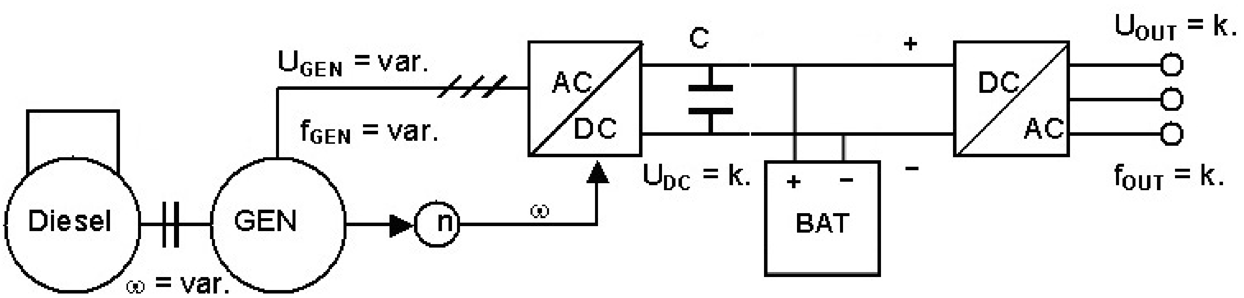

Fig.1. Block scheme of VSCF (variable speed constant frequency) generating set with accumulator battery in inter-circuit to avoid Diesel overload at low speed operation

$$n_1 = \frac{60f}{p} \quad (1)$$

given by frequency and number of poles 2p. The speed increase over synchronism (n> n_1) gives negative slip:

$$s = \frac{n_1 - n}{n_1} \quad (2)$$

and negative torque consequently:

$$M = \frac{3.(R_2'/s)}{\omega_1} \frac{U_1^2}{\left(R_1 + (R_2'/s)\right)^2 + X_k^2} \quad (3)$$

where R and X are winding electrical parameters. From (2) applying (1) the driving speed can be described as:

$$n = \frac{60f}{p}(1 - s) \quad (4)$$

These are general knowledge from basic course. With growing slip grows torque (3) and power, which is:

$$P = M\,\omega \quad (5)$$

Where ω is the mechanical angular speed connected to electrical one $\omega_e = 2\pi f$

$$\omega = \omega_e / p \quad (6)$$

Constant speed AG characteristics are in Fig.2 where can be seen much higher torque of generator then of motor. Graphs are from simple model of two-pole generator with label:

Asynchronous generator		132	S02
3 phases	Y400V	50 Hz	3092/min
5 kVA	9,3 A	3 x 80µF/450V	IP54

2.1 Variable speed generator

Having frequency converter the asynchronous machine can work as generator at any speed and instead of speed control the output power can be controlled by frequency.

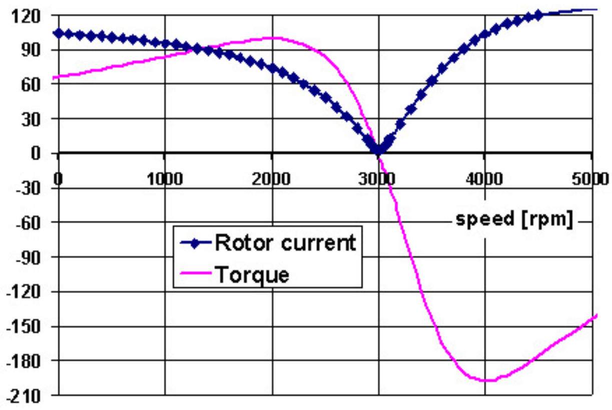

Fig.2 The 2-pole, 3-ph. asynchronous machine model for equivalent circuit parameters: R1=R2'=0,63 Ω, Lk=5,75mH.

At given speed necessary torque can be estimated from (5) and consequently the slip from (3). Slip gives the right frequency using (4)

$$f = \frac{n.p}{60(1 - s)} \quad (7)$$

At any speed of AG can be found such frequency, which is "over-synchronous." The slip calculation from torque (3) has another parameter and it is the voltage. Voltage is frequency dependent:

$$U = k\,\Phi\,f \quad (8)$$

it cannot be kept constant in wide range of speeds because of rapid magnetic flux Φ changes. Flux maximal value is given by integral:

$$\Phi = \int_0^{T/2} u.dt \quad (9)$$

and growing time of period T (decreasing frequency) must be compensated by decreasing voltage (Fig.3).

Flux increase is not possible due to iron saturation; flux decrease means maximal torque decrease because torque is created by flux and armature current as follows:

$$M = \Phi_1 I_2 \sin \varphi_{12} \quad (10)$$

Where φ_{12} is the phase angle between flux and rotor current. To keep constant flux is important for any electrical machine to keep its stability (get sufficient value of maximal torque). That means looking to (8) that with growing speed (and frequency) the voltage must grow too, if we want to keep full torque:

$$\Phi = K\,U / f \quad (11)$$

PMSG has constant flux from the principal.

With constant U/f at low frequencies another problem appears, because there is a difference between terminals voltage and internal "induced" voltage. The characteristics deformation is evident in Fig.4, where are charted 3 mechanical characteristics of AG from Fig.2 with reduced speed. The non-symmetry is clearly visible. Slip in dimensionless quantity defined in (2), it is very handy at constant frequency when n_1 is constant. In

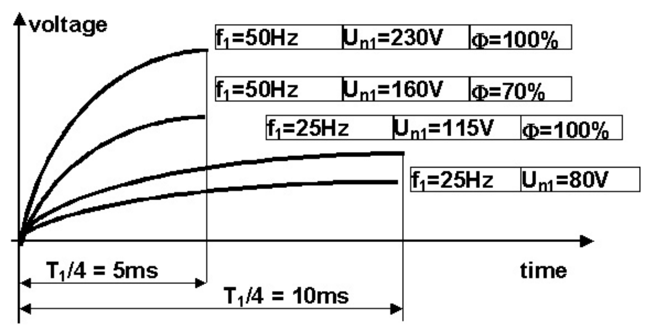

Fig.3 One quarter period of first harmonic voltage wave at reduced frequency and flux

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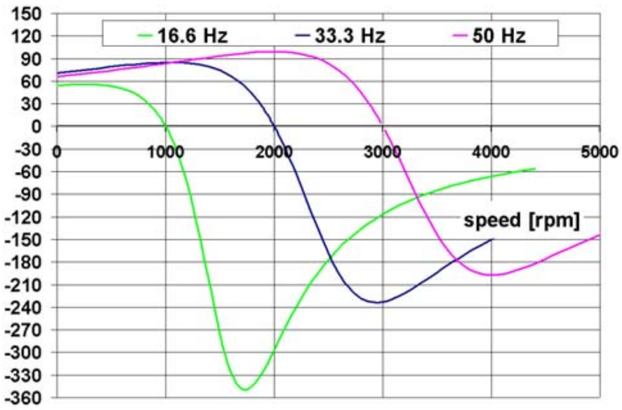

Fig.4 The 2-pole, 3-ph. AG mechanical characteristics with constant U/f for various frequencies

variable frequency applications is more suitable its absolute value Δn [rpm]

$$\Delta n = n_1 - n \qquad (12)$$

It is also speed slip, but it is more common to call it speed difference. In Table 1 is clearly visible how for constant value of Δn changes the value of (relative) slip.

Table 1
Frequency dependent Slip at constant Δn (2p=6)

f	[Hz]	25	50	100	200
s_{Mmax}	[%]	20	10	5	2,5
s_n	[%]	5	2,5	1,25	0,625
n_1	[min^{-1}]	500	1000	2000	4000
n	[min^{-1}]	525	1025	2025	4025
Δ n	[min^{-1}]	25			

There is also presented the value of slip at maximal torque (typical operating point) is calculated from formula:

$$s_{M\,max} = \frac{R_2'}{X_k} = \frac{R_2'}{2\pi f L_k} \qquad (13)$$

For the same torque at any speed and frequency the value of (Δf) ≈ Δn is constant and from measured AG speed can be converter frequency continuously estimated as follow:

$$f = \frac{p}{60}\left(n - \Delta n\right) \qquad M = const$$

Applying (1) on Δn the "slip frequency" Δf can be estimated and added to synchronous frequency calculated from rotor speed.

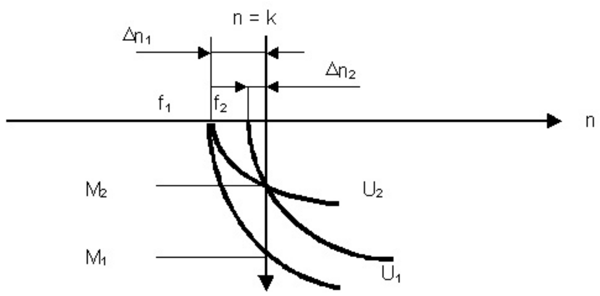

Fig.5 Two ways for the same power – voltage reduction or slip decrease

2.2 Efficiency and Optimal Slip Estimation

The optimal slip determination for maximal efficiency was derived and published in [1] and [2]. Optimal slip Δn can be estimated from efficiency It is evident from Fig.5 that the same value of torque can be reached at lower voltage with higher slip and vice versa.

The entire algorithm for optimal slip estimation is schematically described in Fig.6, for any input power (on the shaft) at any speed. Entry parameters are in the first row.

Data AG:
R1 R2 Lk Pm(n) Img(U/f) Pfe(U/f, f)
INPUT:
P
n
Pm =3e-6*n^2+0,0734*n+2,6
P-Pm
Δn **variable slip step**
ns = n-Δn
s = 1-(n/ns)
f = ns*p/60 Xk = 2PI*f*Lk
Pj2= (P-Pm)*s/(1-s)
Pdel = P-Pm-Pj2
I2=(Pj2/3/R2)^0,5
Z2= ((R2/s)^2+(Xk/2) ^2) ^0,5
U=Z2*I2*1,732 line to line!
sinφ2=Xk/Zk
cosφ j2=((1-(sinφj2) ^2) ^0,5
B= U2*50/f2) proportional to flux / but not B [T]!
Img=9e-7*B^3-0,0006*B^2+0,122*B-6,646
Pfe =(3e-16*B^7,0725)*f/50
Ife=Pfe/U2/3^0,5
I1w=I2*cosφj2-Ife active component of stator current
I1q=I2* sinφj2+Img reactive comp. of stator current
I1=(I1w^2+I1q^2)^0,5
Pj1=3*R1*I1^2
OUT:
P1=Pdel-Pfe-Pj1
η=P1/P

Fig.6 The model for optimal AG slip estimation

For illustration one optimal slip diagram is presented (Fig.7) where the influence to efficiency is evident.

Table 2 Bulk AM digest for 6kW, 3000rpm AG

			RECALCULATED to 2925/min					
n	P_{MOT}	η AM	*** P_{MOT}	P_{1MOT} $=P_{2GEN}$	ΔP	P_{1GEN}	η GEN	m
rpm	W	%	W	W	W	W	%	kg
2925	**5500**	**86,5**	**5500**	**6358**	**858**	**7217**	**88,1**	40,5
1420	*2200*	*82*	*4532*	*5526*	*995*	*6521*	*84,7*	*21,5*
1420	**3000**	**83**	**6180**	**7445**	**1266**	**8711**	**85,5**	24,5
925	**1500**	**74**	**4743**	**6410**	**1667**	**8076**	**79,4**	24
940	*2200*	*78*	*6846*	*8777*	*1931*	*10707*	*82,0*	*27*
680	**1100**	**72**	**4732**	**6572**	**1840**	**8412**	**78,1**	22
705	*1500*	*74*	*6223*	*8410*	*2187*	*10597*	*79,4*	*24*

2.3 Control strategy for AG supply

PWM converter creates switched voltage as is in Fig.8, modulation frequency is tens kilohertz.
Torque control for constant frequency is only voltage dependent, realized by slight modulation changes. All control must keep in long time integral equivalency of the charge from and to the battery.

Some additive problem in this simple wiring makes non-stabile battery voltage which varies in range over 30% as is known from car batteries e.g. 10,5 to 14V for rated value 12V. The voltage on capacitor in the inter-circuit cannot be therefore stabilized; oppositely its disruptive strength must be chosen in agreeable to maximal battery voltage. The influence of battery voltage fluctuation on PWM is illustrated in Fig.8; the values of fluctuation are in Table 3

Table 3 Battery voltage drift

Un [V]	288	576	48	96
Umin [V]	336	672	56	112
Umax [V]	240	480	40	80

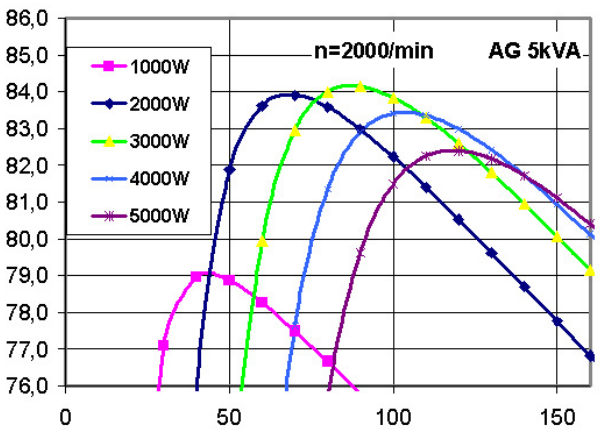

Fig.7 Efficiency vs. slip for variable power

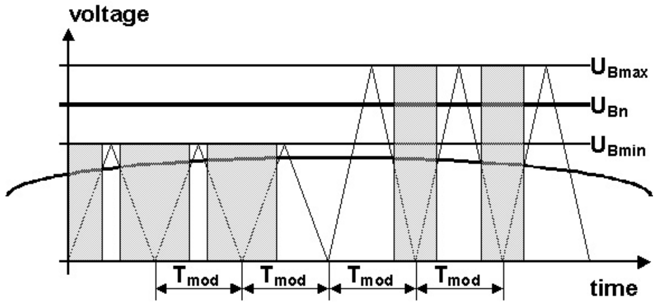

Fig.8 PWM voltage modulation at various battery voltages

For 3-phase output 3x400V was chosen voltage value in inter-circuit 600V and suitable battery was realized from 4 set each from 12 sealed acid batteries for UPS with rated capacity 7 Ah. The battery properties are in Table 4.

Table 4 Battery parameters
Lead acid seald battery discharge energy and power

C_5	I_{max}	Batt	Un	P_{max}	T	max	En.
Ah	A	V	V	kW	min	kJ	kWh
7	20	24 x 12	288	6	10	3600	1
7	20	48 x 12	576	12	10	7200	2
7	20	48 x 12	576	2	120	14400	4
44	120	4 x 12	48	6	10	3600	1
44	20	4 x 12	48	1	120	7200	2
44	20	8 x 12	96	2	120	14400	4

To have sufficient power very big battery capacity must be used

3 Car board-net sources

The maximal power value of board generators is speed independent and this is the main difference to the General Power Systems. If the power does not growth with speed, the flux reduction can be used as well as in common synchronous generators with controlled field. In such case the very high number of pole is not unacceptable, because very high frequency (up to 1 kHz) is compensated by low flux and the iron losses make no problem.

For the typical SG stator with number of poles 2p = 12 are calculations digestedly to be seen in Table 4. The stator can be completely used from the actual SG, and rotor will be replaced by simple cage rotor without any brush contact. Instead of rotor control, the field will be

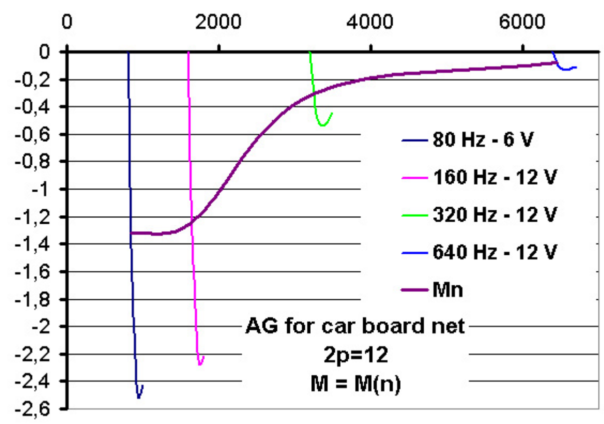

Fig.9. AG for car board net supply

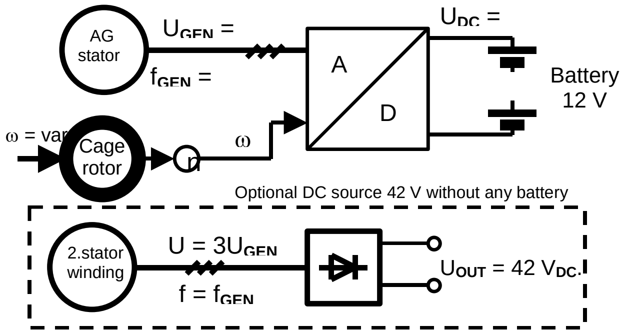

Fig.10. AG with inverter supplies battery and car board net. Optionally non-controlled auxiliary voltage source

reduced at speed elevation by keeping the stator voltage on constant value:

$$U = k\,\Phi\,f = \text{const} \qquad \rightarrow \Phi = \text{variable}$$

Flux and torque reduction does not allow using constant Δn frequency control in accordance with Fig.9. But the slip will be constant as well as rotor losses.

3.1 Multi level voltage

For the second voltage circuit in modern vehicles can be the same AG used, with second winding in the stator of adequate number of turns. This winding can be directly connected to the diode-rectifier, without any battery and other control (Fig.9). The magnetizing current of the machine is completely guaranteed via first voltage circuit, which is always connected to the battery. The arrangement is simpler then in IFPS, because only one converter from Fig.1 is used. The converter must strictly control correct flux value at any load and speed.

4 Conclusions

Asynchronous generator offers high enough efficiency for the use in variable speed generating. It is much more cheep and robust in comparison with PM SG and its control by frequency and voltage from PWM converter is more simple thanks to possible slip variation. The rotor cage can be operated at much higher temperature then NdFeB magnets. The only one disadvantage is the very narrow air-gap, which needs strong shaft and perfect bearings.

Sinusoidal current represents next advantage with positive influence on losses account.

In the automotive industry the AG can offer the brushless generator with higher reliability. AG can also be used in development of gearless starter-generator unit with simple inverter or in new board net systems with two voltages.

Twin windings system can be designed to supply two isolated board circuits of different voltage (14 V and 42 V respectively) with only one control of the primary one, which is battery connected.

The complete problem of battery voltage drift must be more experimentally verified, in this moment only first test are performed.

The low voltage AG can be manufactured with small adaptations in technology, the necessary converter technology becomes cheaper and more reliable from year to year.

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