

Variable Speed Asynchronous Generator

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Abstract. The variable speed power generation brings higher efficiency and other economy benefits namely in low power range sources and isolated systems with local net supply. Typically it is in mobile power generation based on fuel engine drive, but the results are also useful in the area of wind power generation and maybe in few years in automobile industry for car board-net supply as well. To keep high efficiency, the cheap constant-geometry wind turbine must be operated at variable rotation speed in dependence on wind speed. Permanent magnet synchronous generator was first to used in VSCF generation, but its flux cannot be decreased at reduced load, therefore its excellent rated efficiency is not so optimal in competition with much cheaper and robust asynchronous generator (AG) at partial load. The mathematical model for AG optimal slip estimation from efficiency point of view is created. Some model results are presented to show the AG efficiency at varying load and its other advantages.

Key words

Variable speed constant frequency (VSCF) technology, permanent magnet synchronous generator (PMSG), asynchronous generator (AG), efficiency optimization, inverter

1. Introduction

Variable speed power generators are used in wind power plants and in new mobile Diesel GEN-SETS [1], [2], where the output power grows with speed. The torque is approximately constant - Diesel, or growing with speed - wind turbine. In such applications synchronous generator with permanent magnet field (PMSG) is mostly used because of its best efficiency and no need of field control or supply. Power electronics frequency converter must always complement it (Fig.1), to get constant voltage and frequency at the terminals. Asynchronous generator AG for variable speed was few years ago out of reality, because it needs for each frequency different value of parallel capacitor in autonomous run. New converter techniques with active rectifier bring back the idea of use the cheap, simple and robust AG in power generating at variable speed. Inverter control for AG also can be more

simple and not so expensive as for SG, because the synchronism is not strictly necessary.

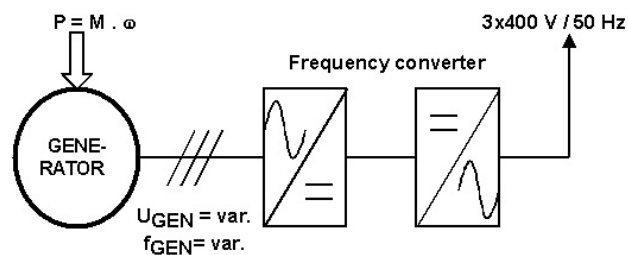


Fig. 1 Block scheme of VSCF (variable speed constant frequency) generating set with indirect - voltage type frequency converter

The road vehicles board net generators are supposed to deliver constant power (maximal) at any speed. Torque is therefore inversely proportional to the speed, and flux should be decreased with the speed grow to keep constant voltage. PMSG is absolutely unsuitable here, because modern engines very wide speed range brings enormous voltage variation at constant field.

The wound rotor SG is therefore used nowadays, with field coil supplied from electronic controller by brushes. The advantage is low-power DC controller for field coil circuit. Stator winding supplies battery (and all the net) via diode bridge rectifier (e.g. DC output). Brush-less generator offers higher reliability and the robust cage rotor AG with integrated AC/DC inverter can replace actual alternator with its field controller and rectifier [3], at minimally equal efficiency and better reliability.

2. Industrial frequency power sources

The typical arrangement of variable speed generating set for constant frequency output is in the Fig.1. Not supposing the use of a commutator AC machine (Winter – Eichberg), the frequency converter is obligatory. Such configured power source with constant frequency (50 Hz) and voltage (400V) output is supposed to

produce more power with growing speed [4]. On the terminals of generating set it appears as the current grow-up indeed, but in generator with constant flux (magnetic product) the grow of power is given by voltage increase and the current keeps on constant (Table I).

TABLE I. Diesel-driven generator with constant flux, 2p=12

Diesel speed n	[r.p.m.]	1000	1500	2000	2500	3000
f_{GEN}	[Hz]	100	150	200	250	300
U_{GEN}	[V]	140	210	280	350	420
P	[W]	2000	3000	4000	5000	6000
I_{GEN}	[A]	10	10	10	10	10
I_{OUT}	[A]	3,3	5	6,6	8,3	10

Constant flux with growing frequency makes the iron losses increase and that is why the maximal frequency should not exceed 400 Hz to keep efficiency and temperature-rise in good values, or to use no iron armature construction.

A. Wind power generation

If the driving torque grows up with the speed, typically in wind power generating, the generator current must grow too, as is clearly visible in Table II. The generator armature winding wire is then designed from the maximal power (and torque) value and at lower speeds is not fully electrically charged.

TABLE II. Wind turbine driven generator with constant flux

Wind speed v	[m/s]	4	6	8	10	12	14
f_{GEN}	[Hz]	80	120	160	200	240	280
U_{GEN}	[V]	120	180	240	300	360	420
P	[kW]	1	3,38	8	15,63	27	42,88
I_{GEN}	[A]	6	13,5	24	37	54	73
I_{OUT}	[A]	1,7	5,7	13,7	26,5	46	73

3. AG generator

Till now there is no difference between the use of PMSG or AG respectively. AC/DC converter for PMSG can be more simple, because PM creates the field lastingly, but AG must be first magnetized by stator winding current, therefore diode rectifier cannot be used on its terminals. If two identical inverter units are used as shown in Fig.2, AG can be used for variable speed generation successfully [5].

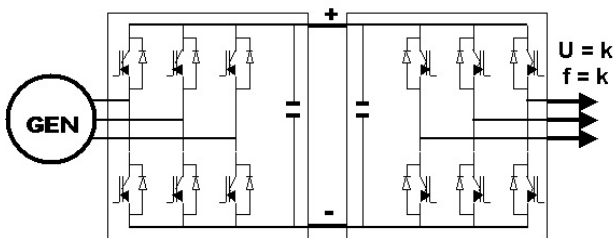


Fig.2 Frequency converter from two identical inverter bridges

Let us suppose that there is in Fig.2 the electrical controlled drive supplied from the terminals on the right side, where voltage and frequency are constant and generator is in motor function starting Diesel. After Diesel starts up, it changes from the load into the source of torque and power and it begins to drive the generator. Modern converter “active front end” [6] with two identical bridge units is able to change its operating quadrant and to deliver the energy “back” into the AC net (recuperation). At any generator speed and voltage, its energy can be inverted to the standard net parameters (400 V, 50 Hz).

If there is no AC net in isolated systems, some other voltage source must be at disposal for charging of inter-circuit capacitors to start the inverter.

For the reverse power flow (from the terminals to AG), the frequency converter is known as a typical converter for AC drives with voltage inter-circuit. In the constant torque control area (under rated frequency) the magnetic flux in AG is kept on the nearly constant value ($U/f = k$). This kind inverter control for the SG must be more accurate, synchronized with rotor position and for correct function it needs the expensive sensor - resolver. Inverter control for the AG is much more simple, because at any frequency which gives non-zero slip the torque M appears.

A. Variable speed AG

Torque is voltage and slip dependent according to the formula:

$$M = \frac{3 \cdot (R_2' / s)}{\omega_1} \cdot \frac{U_1^2}{(R_1 + (R_2' / s))^2 + X_K^2} \quad (1)$$

where the slip s is described by formula:

$$s = \frac{\omega_1 - \omega}{\omega_1} \quad (2)$$

The synchronous speed is:

$$\omega_1 = 2\pi f_1 / p \quad (3)$$

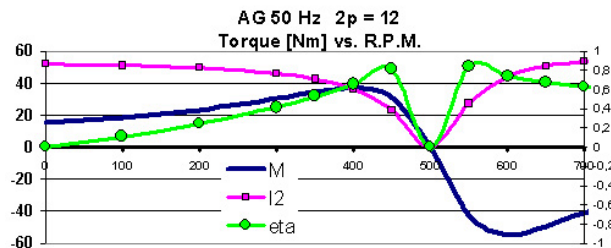


Fig. 3 The 12-pole, 3-ph. AM model for equivalent circuit parameters: $R_1=R_2'=0,1\Omega$, $2\pi Lk = 0,01H$

From the basic theory it is well known the phenomena, which appears if the AM speed increases over the synchronous one

$$\omega > \omega_1$$

The slip is negative

$$s < 0$$

and the torque, which occurs, is negative too (Fig.3). If the AG is connected with the net, which can supply its magnetizing current (to create the magnetic field), it is

able to deliver the electric power, or in autonomous run the local capacitor can be a reactive power source [7]. The complete AC/AC converter represents on the AG terminals the supplied variable frequency net. At any speed of AG can be found such frequency, which is "over-synchronous":

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

because

$$n = \frac{60f}{p} \cdot (1-s) \text{ [RPM]} \quad (5)$$

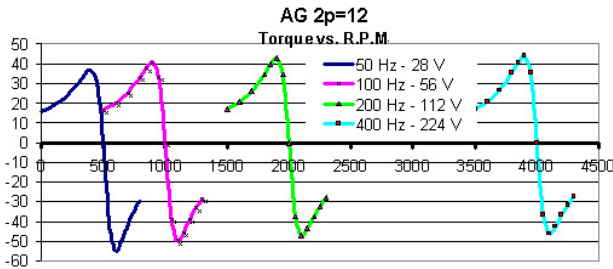


Fig. 4 The AG from Fig.2 at various speeds with constant flux

Better than slip control is Δn control, because the value of s_{Mmax} is frequency dependent (Table III and Fig.4). If for our example AG at 50 Hz the value of $s_{Mmax} = 20\%$ can be easily received, it will be for the same machine at 300 Hz six times less (Table III.), because:

$$s_{Mmax} = \frac{R'_2}{X_k} = \frac{R'_2}{2\pi f L_k} \quad (6)$$

It should be noted, that Δn is the real slip in absolute value, but from historical reasons only its rated value related to fix frequency, $s = \Delta n/n_1$ is well-known and used.

TABLE III. Frequency dependent slip predicts constant Δn frequency control

f	[Hz]	50	100	150	200	250	300	350
s_{Mmax}	[%]	20	10	6,66	5	4	3,33	2,85
s_n	[%]	5	2,5	1,66	1,25	1	0,83	0,7125
n_1	[RPM]	500	1000	1500	2000	2500	3000	3500
n	[RPM]	525	1025	1525	2025	2525	3025	3525
Δn	[RPM]	25						

For the same torque at any speed and frequency the value of $(f \cdot s) \approx \Delta n$ is constant and from measured AG speed can be converter frequency continuously estimated as follow:

$$f = \frac{p}{60} (n - \Delta n) \quad M = \text{const} \quad (7)$$

It is in good agreement with the calculation of rated rotor losses (Joule). If the power increase is given only by the voltage component at the same current, the rotor winding losses must be speed independent

$$\Delta P_2 = 3 \cdot R'_2 \cdot I_2'^2 = \text{const} \quad (8)$$

and from the function

$$\Delta P_2 = s \cdot P_\delta \quad (9)$$

the slip must decrease with increasing output power (Table III.).

B. AG control

The asynchronous motor can convert to the generator at constant frequency supply, when its speed becomes higher, then the speed of stator field (Fig.3). Then the stator current grows up again, but it moves into 4-th quadrant (Fig.8) and the power orientation is revolved. At any speed the asynchronous machine can work as AG, if it is supplied by variable frequency, which creates the stator field speed slower, then the rotor's one is.

At the constant rotor speed n , for half-power reduction, the torque must be reduced from M_1 to M_2 (Fig.5). It is possible either by frequency change from f_1 to f_2 with constant voltage, or at the same frequency f_1 by voltage reduction to U_2 . In the first case it brings smaller slip and high flux, in the second higher slip losses, but consequently smaller iron losses thanks reduced flux. Total losses optimizing by voltage and slip variation is the aim of the next.

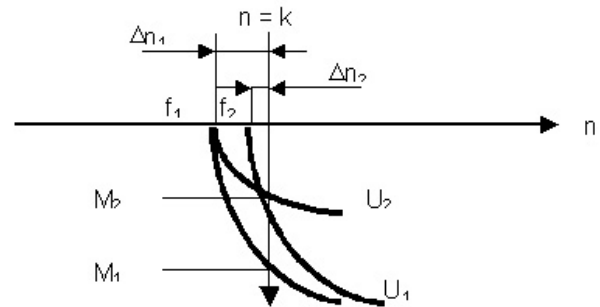


Fig.5 Power reduction of AG at constant speed by voltage or frequency

4. VSCF Diesel GEN-SET

The first models of variable speed power sources were mostly designed with synchronous generator (SG) and because the field control is not necessary in this application, the permanent magnet (PM) excitation was used with advantage. Such generator (PMSG) reaches best efficiency (with full load), but it is very expensive in manufacture and its PM from rare earth are very sensitive to higher temperature. Passive rectifier is the advantage in acquisition price, but DC/DC step-up converter must complete it (Fig.6); which represents another block of energy conversion and additional losses in compare with active pulse rectifier. Also non-sinusoidal current from generator to diode rectifier causes additional losses in armature winding.

The power conversion is obligatory, for constant frequency output but attached frequency converter decreases the total efficiency. Therefore all components

of power flow must be carefully optimised to reach better parameters then in constant speed generation.

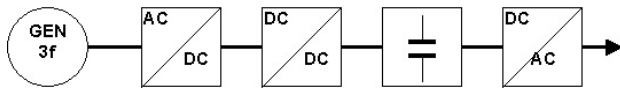


Fig.6 Frequency converter with diode rectifier must have additional DC/DC converter bloc

The variable voltage and frequency of generator is in the first block of converter inverted to the constant value DC voltage in inter-circuit (Fig.1). Having the inverter bridge in the function of active front-back rectifier (Fig.2), the asynchronous generator (AG) can be used too, with many advantages (mechanical and thermal strength, low price, good market offer, simple control etc.). Its only one disadvantage is its rotor winding (cage) joule losses in addition, which are slip dependent, but it can work with reduced flux density and reduced iron losses consequently with optimal slip (and voltage) to reach comparable efficiency oppositely to PMSG.

A. AG versus PMSG

The advantage of synchronous generator with permanent magnets (PMSG) is its highest efficiency because of no rotor losses. Oppositely the asynchronous generator (AG), with the same stator dimensions and the same flux density in the air gap, has thanks the magnetizing current component higher stator current (always with inductive power factor) at equal output power. But moreover it has the slip losses in the rotor winding (Fig.7).

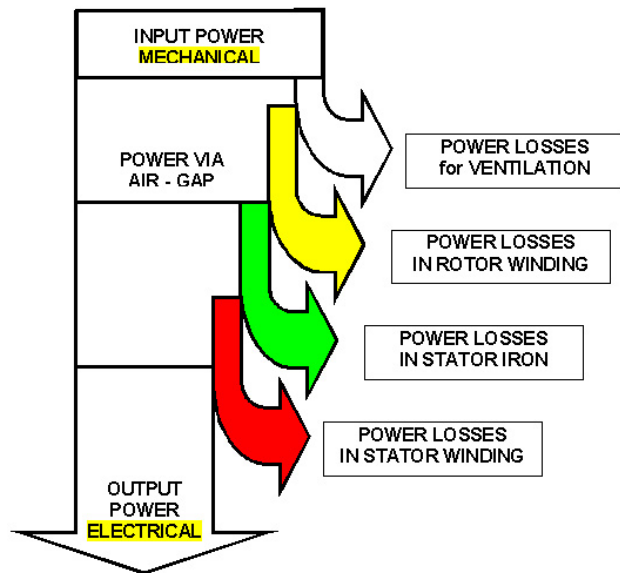


Fig.7 Power flow diagram of AG

There are also some disadvantages of PMSG, which must be taken into account. First it is constant flux at any load, which is not optimal at low power. To minimize total losses there is better some small flux (and voltage) decrease with consequent important iron losses reduction, and only little current (and joule losses) increase. AG flux control is very easy.

Then it is operating frequency, which is much higher for PMSG. For typical driving speed 3000 rpm the common 4-pole AG works with frequency about 100 Hz, PMSG because of the PM stability [8] must have at least 10-poles with frequency 250 Hz, or better 12 poles with frequency 300 Hz.

Inverter control of SG must be much more precise to keep the SG in synchronism. Also the price of SGPM appears to be its disadvantage, as well as its low thermal strength, which needs better rotor ventilation.

B. Numerical model of AG

The main purpose of this work is to find some possible control rule with non-constant Δn for variable speed and power input to minimize total AG losses. The numerical model of AG was therefore prepared to optimize the efficiency. The computational method of optimal slip estimation for given values of mechanical power and speed will be presented later.

The calculations are based on slip variation and sequential evaluation of all losses components, which are subtracted from mechanical power input. The resulting electrical power output maximum gives the right value of slip and stator frequency for any speed and power (or torque) input.

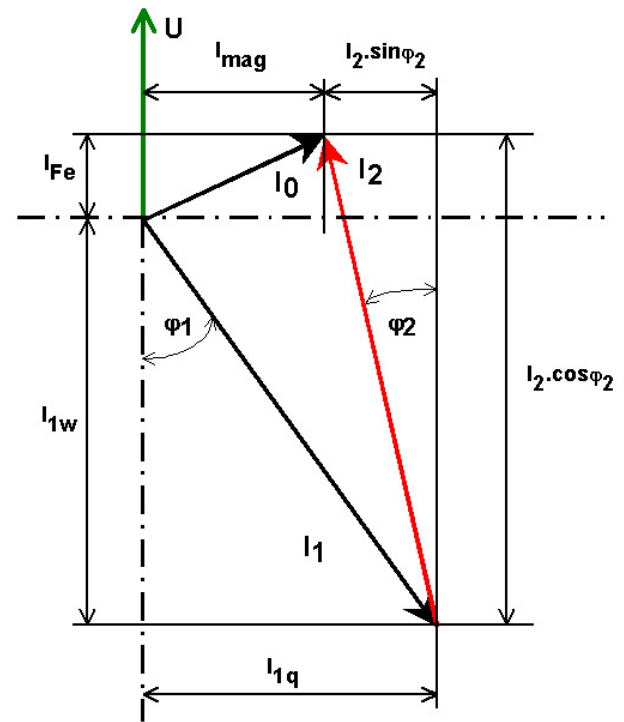


Fig.8 Vector diagram of AG

The common simple method of power control based on constant slip ($\Delta n = \text{const.}$) used in electrical drives for asynchronous motors braking [9] gives not optimal output power. The frequency is calculated from the measured rotor speed and Δn , which is usually equal to nominal value:

$$\Delta n = 60.f/p - n_n \quad (10)$$

Then the frequency is:

$$f = p (n - \Delta n)/ 60 \quad (11)$$

Vector diagram of AG in Fig.8 is the basis of numerical model. The model developing structure is in Fig.9, where are AG data are first asked, then input power and speed.

Data of AG:

R1 R2 Lk
Pm(n) Img(U/f) Pfe(U/f,f)

INPUT:
P
n

$P_m = 3e-6n^2 + 0,0734n + 2,6$
P-Pm

Δn **variable slip**

$n_s = n - \Delta n$
 $s = 1 - (n/n_s)$
 $f = n_s \cdot p / 60$ $X_k = 2PI \cdot f \cdot L_k$

$P_{j2} = (P - P_m) \cdot s / (1 - s)$
Pdel = P - Pm - Pj2
 $I_2 = (P_{j2} / 3 / R_2)^{0,5}$
 $Z_2 = ((R_2 / s)^2 + (X_k / 2)^2)^{0,5}$
 $U = Z_2 \cdot I_2 \cdot 1,732$ line to line!
 $\sin \varphi_2 = X_k / Z_k$
 $\cos \varphi_2 = ((1 - (\sin \varphi_2)^2)^{0,5})$
 $B = U^2 \cdot 50 / f^2$ property

proportional to flux density / but not B [T]!
 $Img = 9e-7 \cdot B^3 - 0,0006 \cdot B^2 + 0,122 \cdot B - 6,646$
 $Pfe = (3e-16 \cdot B^{7,0725}) \cdot f / 50$

$I_{fe} = Pfe / U^2 / 3^{0,5}$
 $I_{1w} = I_2 \cdot \cos \varphi_2 - I_{fe}$ active component of stator current
 $I_{1q} = I_2 \cdot \sin \varphi_2 + Img$ reactive component of stator current

$I_1 = (I_{1w}^2 + I_{1q}^2)^{0,5}$
 $P_{j1} = 3 \cdot R_1 \cdot I_1^2$

OUT:
 $P_1 = P_{del} - Pfe - P_{j1}$
 $\eta = P_1 / P$

Fig.9 AG numerical model structure

All parameters are from experiments on 2-pole AG from our laboratory, with label:

MODECO	Asynchr. Generator	132	S02
3 phases	Y 400 V	50 Hz	3042/min
5 kVA	9,3 A	3 x 80 μF/450 V	IP54

This AG may be the remake, based on bulk motor AM from Table IV. The constant parameters (R, L) are easy to be obtained from standard tests. Three other parameters (Pm, Imag, Pfe) are speed and flux density respectively dependent and they must be mathematically described. The used polynomial or exponential functions are the result of many trials.

The approximation of iron losses at 50 Hz supply is plotted in Fig.10. For simple linear recalculations to other frequencies the eddy-current losses are neglected and all iron losses are supposed only from hysteresis.

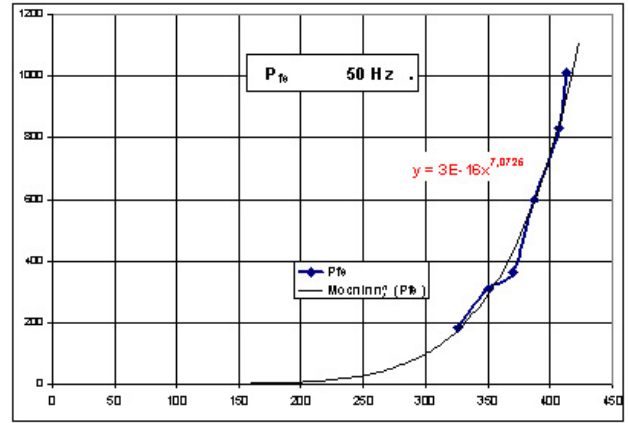


Fig.10 Measured iron losses and their exponential substitution

Every power input has its own data sheet in EXCEL™ model [10]. The Δn variation up to 5% of rated speed is enough for standard AG and from results it is clearly to be seen that optimal Δn is between 1 and 3%. Besides of efficiency the right value of frequency and voltage can be plotted, as is in Fig.11.

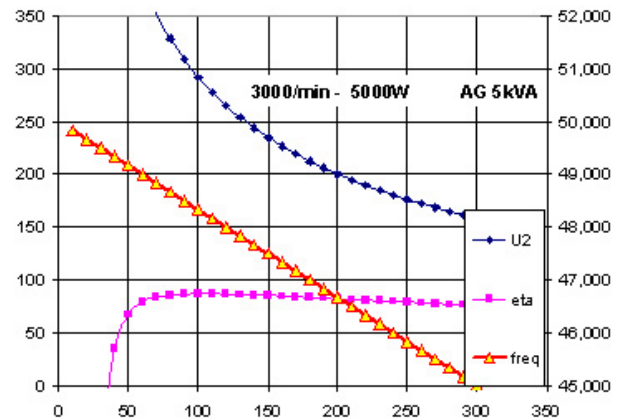


Fig.11 Slip dependence of AG inputs and efficiency

5. AG analyses Results

The graphs for optimal Δn control from efficiency point of view are created from numerous data sheets. Here they are presented three of them for driving speed 1000, 2000 and 3000 rpm respectively in Fig. 12, from where two results can be observed.

- Optimal frequency control of investigated AG can bring efficiency improvement in the frame of 5 %
- The load decrease always needs Δn decrease, which means small frequency increase, as was supposed.

It is clear still from Fig.11 that nominal voltage value (400V) gives very low slip and efficiency too, because of over-saturation of AG iron.

Optimal AG output voltage speed dependence for various power input is in Fig. 13. For simple orientation there are two lines charted there for 400V/50Hz and 380V/50Hz respectively. Similar dependence of AG output voltage

versus input power with constant speed parameter is in Fig.14.

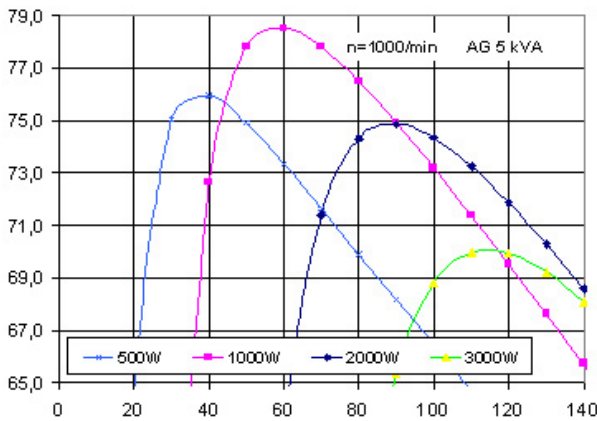


Fig.12a AG efficiency [%] vs. slip Δn , at 1000 RPM

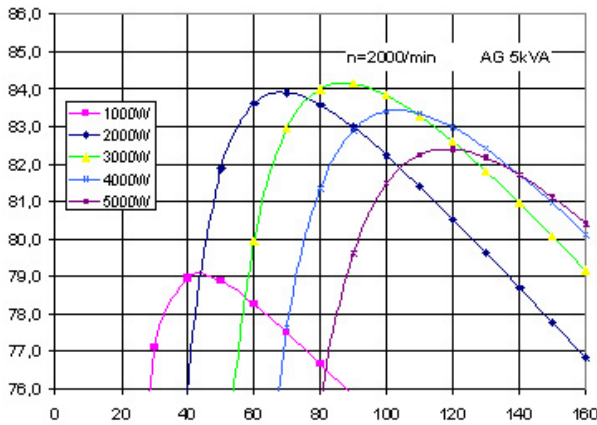


Fig.12b AG efficiency [%] vs. slip Δn , at 2000 RPM

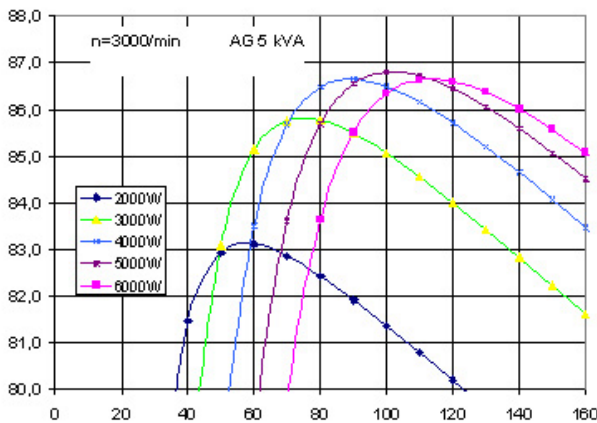


Fig.12c AG efficiency [%] vs. slip Δn , at 3000 RPM

The comparison of AG vs. PMSG efficiencies can be done from Fig.15 and 16. The PMSG is only hypothetical with the same number of poles, the same armature winding with no loss in its rotor. The rotor is so PM equipped to create field, which induce nominal voltage at nominal frequency. It is not the optimal construction and this is the reason of so bad PMSG results.

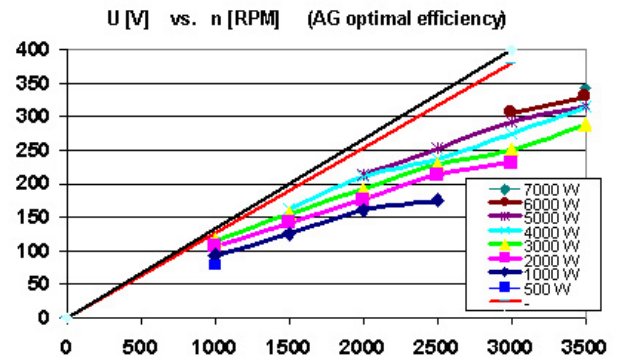


Fig.13 Output voltage regulation of optimised AG

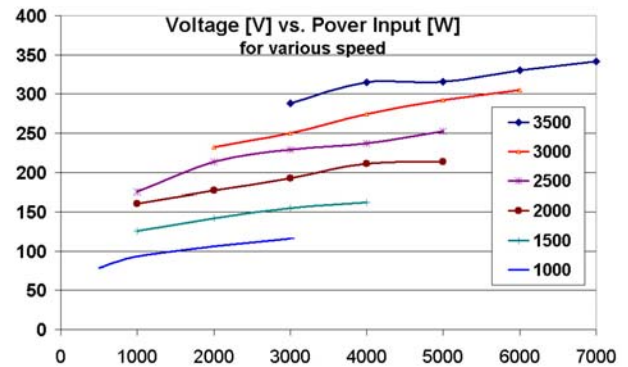


Fig.14 Output voltage of optimised efficiency AG

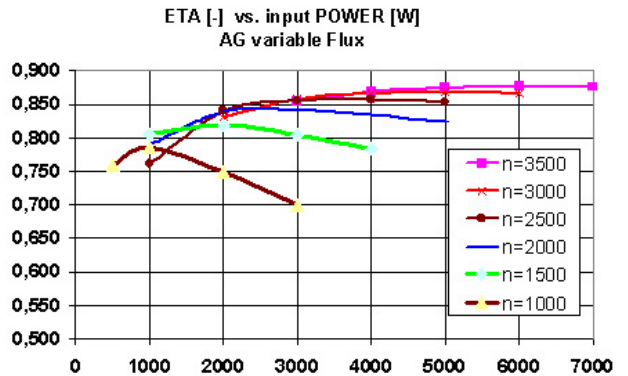


Fig.15 AG optimal efficiency

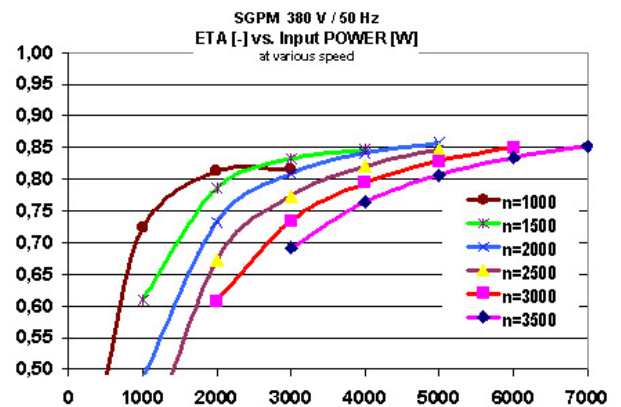


Fig.16 Efficiency of SGPM with AG equal parameters

AG power factor is highly surprising (Fig.17), because the flux reduction reduces also the reactive component of current. From this analysis results, that practically no joule losses rise will appear due to power factor.

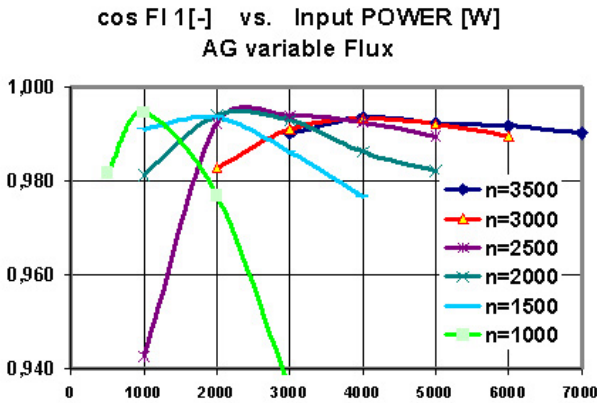


Fig.17 Power factor of optimised efficiency AG

Speed reduction brings worse ventilation and heat transfer, total losses are also decreased but constant current means constant copper losses in armature winding. The AG in wind power generation has no problem, in Diesel driven GEN-SETS must be current observed too, and this dependence can be seen in Fig.18.

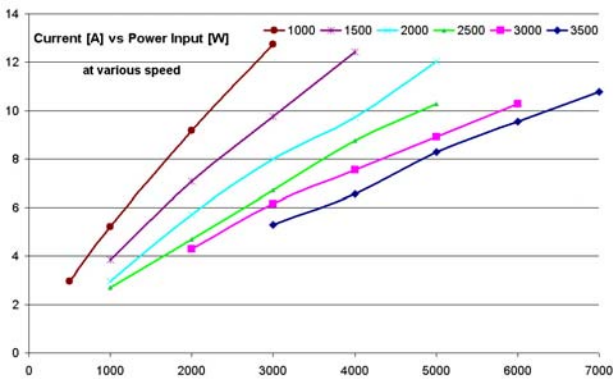


Fig.18 Current from optimised efficiency AG

A. AG choice

One of AG advantages is its price and wide choice on market. All asynchronous motors (AM) can work as generator without any special requirements for torque curve shape, because AG always works near to synchronous speed.

To right dimensioning it is important not forget the fact, that on the AM label is its mechanical power output. Electrical input power is in the size range, which is interesting for small power sources 1- 20 kW, about 15% more (Table IV) and on the shaft of AG it is next 15 % power more from driving engine. A 7 kW Diesel can drive AG with electric output over 6 kW with label power 5,5 kW.

For higher frequency AG needs only better rotor balance. If four-pole AG is driven by 3000 RPM its frequency will be 100 Hz and with delta-connected stator winding there

is no more remake necessary. AM 5,5 kW 2925 T, 400 V/Y can be so replaced by AM 3 kW, 1400T 220 V/D and it is only slightly demagnetized machine from bulk production.

TABLE IV. Survey of two-pole bulk AM

Pmot	ETA mot	P1mot =P2gen	ΔP	PIG	η GEN	I l	cosφ1	n
W	%	W	W	W	%	A	---	RPM
1500	79,0	1899	399	2297	82,6	3,22	0,85	2860
2200	82,0	2683	483	3166	84,7	4,55	0,85	2880
3000	84,0	3571	571	4143	86,2	6,06	0,85	2890
4000	86,0	4651	651	5302	87,7	7,80	0,86	2905
5500	86,5	6358	858	7217	88,1	10,31	0,89	2925
7500	88,0	8523	1023	9545	89,3	13,82	0,89	2930
11000	89,5	12291	1291	13581	90,5	20,15	0,88	2940
15000	90,2	16630	1630	18259	91,1	26,66	0,9	2940

6. Car board-net sources

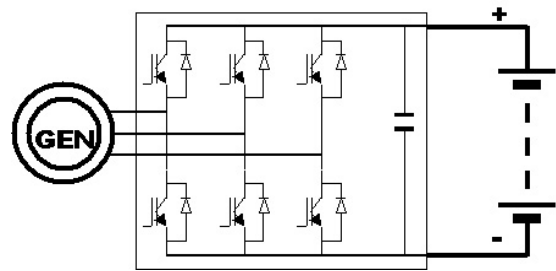


Fig.19 Car board net power source based on AG

Maybe it is a little out of topic, but mostly used variable speed generators are car alternators. The big advantage of AG in here is its much simple rotor and continuous presence of accumulator battery means no trouble with inverter initialization. Only the price of inverter is limiting now, but generally the prices of electronics are rapidly decreasing and in few years the car supply will be realized by AG as is in Fig.19 or, may be with higher torque and power only one combined machine will serve as generator and starter.

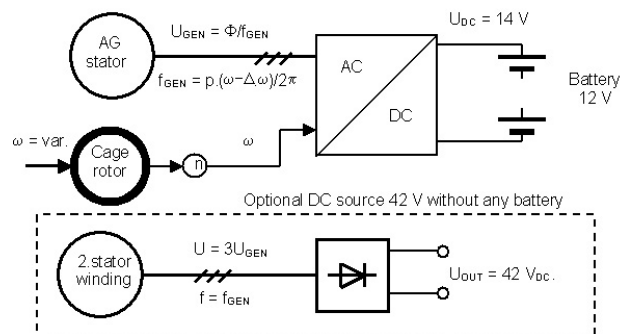


Fig.20 Two voltage nets source based on AG

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 [3]. The second one has stabilized voltage and supplies simple diode bridge (Fig.20). Survey of voltage, current frequency and flux in all the speed range is clearly from Table V.

TABLE V. AG flux decrease for constant power output

n [rpm.]	800	1200	1600	2000	4000	6000	8000	10000	12000
f_{max} [Hz]	80	120	160	200	400	600	800	1000	1200
U_{GEN} [V]	8	12	16	16	16	16	16	16	16
I_{maxGEN} [%]	100								
I_{maxNET} [%]	50	75	100						
Φ/Φ_{max} [%]	100	100	100	80	40	26	20	16	15

7. Conclusion

The model results are in good agreement with theoretical expectations, the laboratory verification is not still completed. First laboratory test are oriented to the voltage control in inter-circuit and starting of inverter without AC net on the output side.

All here presented result are only for one two-pole AG, which is not optimal for low speed applications, but it was to disposal in our laboratory and it can work with our Diesel. The next models are supposed to be realized from four and six poles machines respectively, with reduces power, where better efficiency is supposed.

The parameters of standard asynchronous machines, which are published by manufacturers for customers, are not sufficient for the presented model input. Some of them must be reached by laboratory tests or received from designer's calculations.

The comparison with SGPM has been realized only in the simplified version of hypothetical machine with equal stator.

Our laboratory model new frequency converter consists from two identical professional inverter units connected in their DC inter-circuits (Fig.2). The vector control can be used too without any speed loop and torque control derived from inter-circuit voltage is still verified.

Asynchronous generator offers high enough efficiency for the use in variable speed generating. It is much more cheap and robust then PMSG and its control in active back front converter is more simple. The rotor cage can be operated at much higher temperature then NdFeB magnets. The only one disadvantage is very narrow air-gap, which needs strong shaft and perfect bearings.

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. The low voltage AG can be manufactured with small adaptations in technology of actual alternators, the necessary converter with MOSFET is also very

simple and technology becomes cheaper and more reliable from year to year.

The complete problem of ventilation and heat transfer is not solved in here; the Joule losses thanks very high power factor are better then supposed, and iron losses reduction can be solved successfully.

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