Low power asynchronous generator analysis

VÍT BRŠLICA
Department of Electrical Engineering
University of Defense in Brno
Kounicova 65, 612 00 Brno
CZECH REPUBLIC
http://www.unob.cz

Abstract: - The presented analysis is based on practical results of low power asynchronous generator in the physical model. The tests of variable speed generating set with asynchronous generator and inverter disclose bad efficiency. Inadequately big value of magnetizing current inhibits the exploitation of the bulk asynchronous motor in generator function with appropriate electrical power output. Even at twice higher speed 3000 RPM this machine cannot give the same electric power output, as is its nominal electrical input in motor run at speed 1415 RPM.
Key-Words: - Asynchronous generator, Theoretical analysis, Efficiency, Model

1 Introduction

The very bad results of output power quantity received from practical test of low power generating set physical model with asynchronous generator and inverter forced us to study more preciously the problems of variable speed asynchronous generator and the results may be interesting for more potential users, who can plan to use this simple machine not only in motor, but in generator run too.

The typical torque characteristics asymmetry is well known (Fig.1) and gives the idea of much higher power in the generator area, which is not correct, such high power is only the message that this machine can accept big mechanical input power (in braking) but there is no information here about the electrical output quantity and the efficiency consequently, which is absolutely important for the generator.

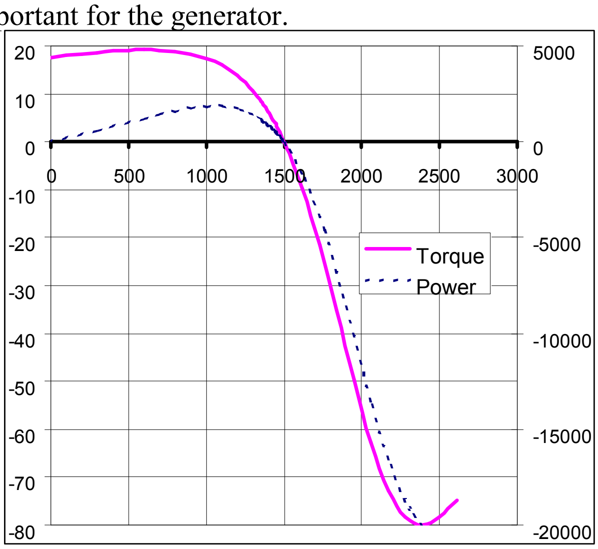

Fig.1 Characteristics of asynchronous machine 1,1kW, 1420 rpm in motor and generator run received by simple mathematical model from basic parameters. The great asymmetry is evident; generator torque is for times greater

The low power machine properties are very suitable for the studies, because the influence of winding impedance is more visible, then in big power machines with efficiency near to 100%.

The parameters of the used machine are in Table 1. It is common bulk machine recoiled to ten times lower voltage and ten times higher current consequently.

Table 1.

1LA70 90 -4AA 90		**1,1 kW**	1415 RPM
23/40 V	**46,5/27 A**	R_1=	0,100 Ω
cosφ = 0,8	eta = 77%	R_2=	0,096 Ω
ik = 4,6	**7,4 Nm**	X_K=	0,129 Ω
p_Mk = 2,3	$p_M$max = 2,4	J = 0,0028 Nm	12,3 kg

The electrical input power into the stator winding is:

$$P_1 = P/\eta = 1100/0{,}77 = 1430\text{W} \qquad (1)$$

Because such value is unavailable, the more detailed analysis is necessary. Some results from the tests at rated frequency 50Hz are in Fig.2.

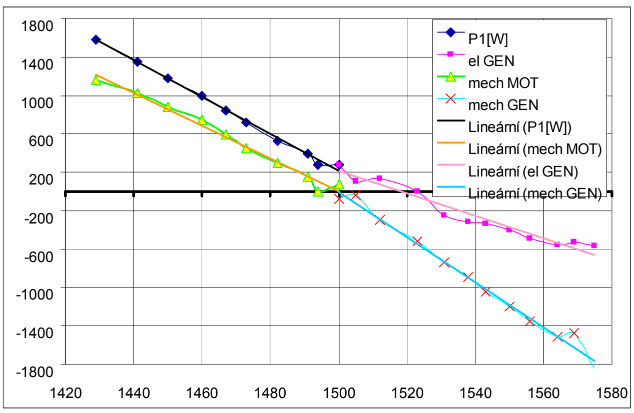

Fig.2 Characteristics of power input and output for AM 1,1kW, 1420 rpm, at 50Hz in motor and generator run shows abnormal great sum of losses in the over synchronous speed area (generator)

In the sub-synchronous area of AM is electric power input higher then the mechanical power output and the difference represents the sum of losses in machine, which is supposed in the ventilation calculi and which causes allowable temperature rise in machine for its lifetime. Therefore the great divergence in power input (mechanical) and power output (electrical) in the over-synchronous area shows not only bad efficiency, but also much reduced maximal power due to overheating. The detail of measured characteristics in the area near synchronism, where it can be linearized, including the mathematical description is in Fig.3.

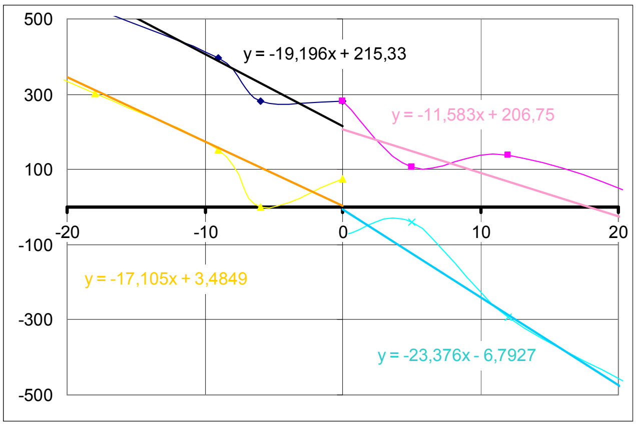

Fig.3 Power [W] vs. speed [RPM] Characteristics at 50Hz with mathematical description of input and output power (directions of linear functions are interesting)

The reasons of such AG bad properties as well as the method of its analysis are described in the next.

2 Asynchronous machine theory

The equivalent circuit of asynchronous machine is very simple with only 4 linear and 2 nonlinear elements, connected into typical T-network (Fig.4). The linear are:

R_1, R_2 stator and rotor winding resistance,

X_{1k}, X_{2k} leakage reactance,

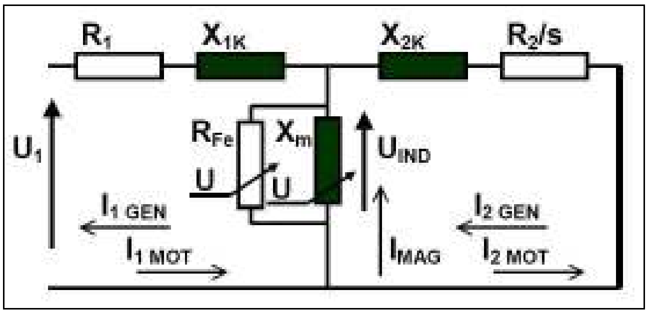

Fig.4 Standard equivalent circuit for investigated AM at 50Hz with currents and voltages description

The nonlinear ones are in the middle branch connected with core magnetizing and iron losses:

R_{fe} iron and friction losses equivalency,

X_{mag} reactance creating the linkage flux

From this network can be vector diagram charted and the transition from motor to generator gives the inversion of rotor current direction (polarity), which causes also the different ratio between the terminals voltage and the internal voltage, which is induced by linking flux. Better then word description it can be seen in Fig.5.

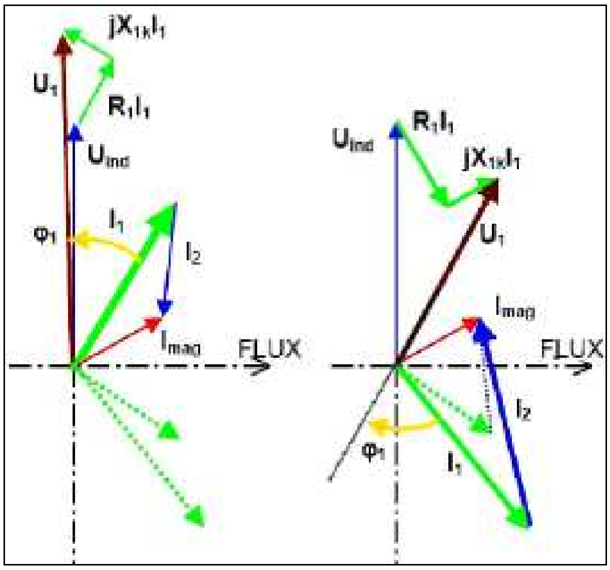

Fig.5 Vector diagram for investigated AM 1,1kW, 1420 rpm, at 50Hz in motor and generator run shows the voltage decrease under the synchronous speed area (generator)

In the both cases the same flux is supposed and also the same value of stator current. But the power situation is radically different because in the generator mode the stator power factor is very low ($\varphi_1 \approx 90°$).

Maybe the voltage drop triangle is not typical because the great machines have the ratio R_k/X_k = 1/3, but the small power machine has nearly inverted value, in our one it is ($R_k/X_k = 3/2$).

After the theoretical analysis the numerical approach only can give us the quantitative results and the answer how to optimize the voltage to maximal efficiency.

3 AG Model

The generator modeling can be optimally started from the rotor, where the mechanical power P_{IN} is changed into the electrical power P_2 and first losses are appearing – the mechanical (friction and ventilation) and the Joule losses in the rotor winding (cage) caused by rotor current.

All the electrical power in rotor P2 is:

$$P_2 = P_{IN} - P_{mech} \quad (2)$$

The power transformed (induced) from the rotor to the stator via the air gap P_δ depends on the slip

$$P_\delta = P_2 (1-s) \quad (3)$$

The slip is defined

$$s = \Delta n / n \qquad (4)$$

where:

$$\Delta n = n_1 - n \qquad (5)$$

n… rotor speed

n_1… speed of rotating field (synchronous speed)

The synchronous speed is frequency dependent

$$n_1 = 60\, f / p \qquad (6)$$

Generator is always operated with negative slip (s, Δn). From the known (or given in here) rotor current the value of P_δ can be calculated:

$$P_\delta = (3\, R_2/s)\, I_2^2 \qquad (7)$$

In the stator are from the P_δ power subtracted the losses in the iron represented in Fig.4 by R_{Fe} element, or in the vector diagram Fig.5 by active component of I_{mag}. The Joule losses in the stator winding can be easily calculated:

$$P_{J1} = 3\, R_1\, I_1^2 \qquad (8)$$

3.1 Rotor circuit

If the analysis is based on constant Ui, for every given rotor current I2 can be easily found the single value of the slip using the Thales circle property (Fig.6).

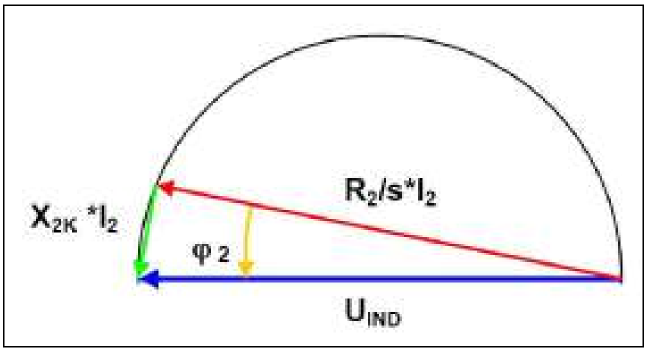

Fig.6 Vector diagram for rotor circuit can be described as a Thales circle configuration

3.2 Internal voltage

The induced voltage Ui is created by the stator supply and very simply it can be described by equation:

$$Ui = k\, \Phi\, f \qquad (9)$$

Where flux Φ is proportional (nonlinearly) to the magnetizing current. If the frequency f is twice higher and the voltage Ui remains the same, the flux must be one half of the original one and the magnetizing current is also reduced.

What grows up with the frequency, it is the leakage reactance, because

$$X_K = 2\, \pi\, L_K$$

And also the voltage drop between the terminal voltage and internal voltage must grow up with increasing frequency.

3.3 Modeling strategy

On the basis of set of equations (2) – (8) with knowledge of the geometry in complex plain from Fig.5 the program was prepared for the AG load ability estimation.

The set of rotor currents is examined for getting the rotor power and corresponding slips. Also the rotor power factor is estimated and it value is really very good as can be seen in Table2.

Table 2.

Ui=19V, 50Hz

i_2 A	XI_2 V	s ---	Pδ W	P_{IN} W	$\cos\varphi_2$ ---	$\sin\varphi_2$ ---	n RPM
-3	-0,194	0,015	171	174	-1,000	0,01	1522
-6	-0,387	0,030	342	352	-1,000	0,02	1545
-9	-0,581	0,045	513	536	-1,000	0,031	1568
-12	-0,774	0,061	683	725	-0,999	0,041	1591
-15	-0,968	0,076	854	919	-0,999	0,051	1613
-18	-1,161	0,091	1024	1117	-0,998	0,061	1636
-21	-1,355	0,106	1194	1321	-0,997	0,071	1659
-24	-1,548	0,122	1363	1529	-0,997	0,081	1682
-27	-1,742	0,137	1533	1742	-0,996	0,092	1705
-30	-1,935	0,152	1701	1960	-0,995	0,102	1728
-33	-2,129	0,168	1869	2183	-0,994	0,112	1751

Table 3.

Ui=19V, 50Hz

i_2 A	i_1 A	cosφ I_1 ---	U1 V	cosφ U_1 ---	P_1 W	eta %	Δn RPM
-3	21,66	0,05	20,6	0,99	73	-41,86	22,7
-6	21,80	-0,08	20,4	0,99	-110	31,35	45,4
-9	22,40	-0,22	20,1	0,99	-288	53,78	68,2
-12	23,43	-0,33	19,8	0,99	-461	63,60	91,0
-15	24,84	-0,44	19,6	0,99	-629	68,44	113,8
-18	26,58	-0,52	19,4	0,99	-792	70,84	136,6
-21	28,57	-0,59	19,1	0,98	-950	71,88	159,5
-24	30,78	-0,64	18,9	0,98	-1103	72,11	182,5
-27	33,17	-0,69	18,7	0,98	-1252	71,81	205,5
-30	35,70	-0,72	18,5	0,97	-1396	71,20	228,5
-33	38,35	-0,75	18,3	0,97	-1536	70,35	251,6

In the Table.3 is the second set of results (the continue of Table.2) with stator current voltage and power factors. At higher slip can be received sufficient value of electrical power output from the stator, but at higher current than is the nominal one, that means the overheating of the stator coils, moreover the value of the efficiency is also worse that the rated one (77%), what indicates problems with overheating in all the machine.

Table 4.

Ui=19V, 100Hz

i_2	XI_2	s	Pδ	P_{IN}	$\cos\varphi_2$	$\sin\varphi_2$	n
A	V	---	W	W	---	---	RPM
-3	-0,387	0,015	171	174	-1,000	0,02	45,4
-6	-0,774	0,030	342	352	-0,999	0,041	91,0
-9	-1,161	0,046	512	535	-0,998	0,061	136,6
-12	-1,548	0,061	682	723	-0,997	0,081	182,5
-15	-1,935	0,076	851	915	-0,995	0,102	228,5
-18	-2,322	0,092	1018	1112	-0,993	0,122	274,9
-21	-2,709	0,107	1185	1312	-0,990	0,143	321,6
-24	-3,096	0,123	1350	1516	-0,987	0,163	368,7
-27	-3,483	0,139	1513	1723	-0,983	0,183	416,3
-30	-3,87	0,155	1674	1933	-0,979	0,204	464,4
-33	-4,257	0,171	1833	2147	-0,975	0,224	513,2

Table 5.

Ui=19V, 100Hz

i_2	i_1	$\cos\varphi$ I_1	**U1**	$\cos\varphi$ U_1	P_1	eta	Δn
A	A	---	**V**	---	W	%	RPM
-3	21,57	0,05	**22,0**	1,00	78	-44,66	3045
-6	21,43	-0,08	**21,7**	0,99	-118	33,45	3091
-9	21,59	-0,22	**21,4**	0,99	-307	57,35	3136
-12	22,06	-0,35	**21,1**	0,99	-490	67,72	3182
-15	22,80	-0,47	**20,8**	0,99	-666	72,72	3228
-18	23,82	-0,58	**20,5**	0,98	-834	75,04	3274
-21	25,08	-0,67	**20,1**	0,98	-995	75,8	3321
-24	26,57	-0,75	**19,8**	0,98	-1148	75,71	3368
-27	28,25	-0,81	**19,4**	0,97	-1292	74,96	3416
-30	30,11	-0,86	**19,1**	0,97	-1427	73,78	3464
-33	32,13	-0,90	**18,7**	0,96	-1552	72,29	3513

The next set of calculations is prepared for the maximal speed of generating set with the frequency f = 100Hz. As was mention before, the internal voltage is kept constant Ui = 19V, therefore the flux is reduced and consequently the magnetizing current, respectively its reactive component. The rotor and stator circuit conditions are digestly presented in Table.4 and Table.5, with better results than at nominal frequency and full flux.

The graphical presentation of the efficiency dependence on the slip and also the stator voltage, stator current and speed increase is in Fig.7 for the rated frequency 50Hz. Similarly are the same properties dependence presented in the graph in Fig.9.

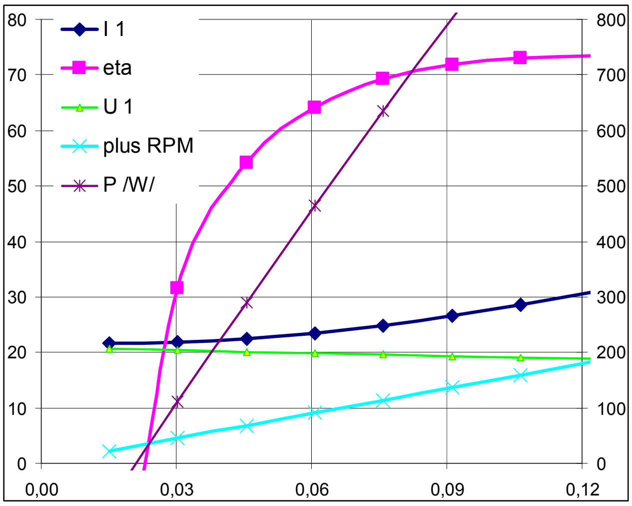

Fig.7 Characteristics of AG 1,1kW, 1420 rpm, output at 50Hz and constant flux with Ui = 19V. Left scale is for stator current I1, efficiency eta, terminal phase voltage U1, the right scale is for electric output power P/W/ and speed increase "plus RPM", horizontally is the slip s

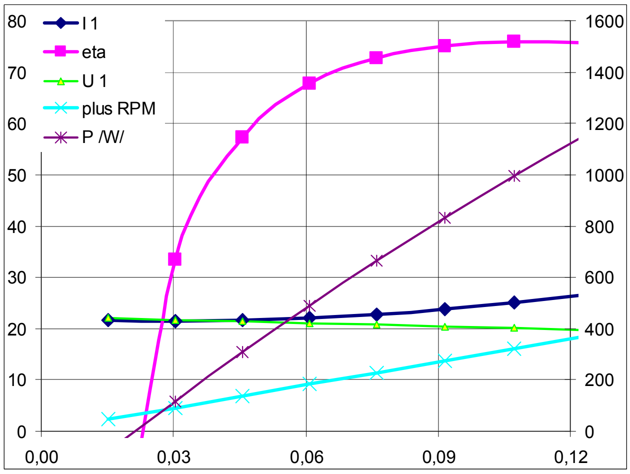

Fig.8 Characteristics of AG 1,1kW, 1420 rpm, output at 100Hz and constant flux with Ui = 19V. Left scale is for stator current I1, efficiency eta, terminal phase voltage U1, the right scale is for electric output power P/W/ and speed increase "plus RPM", horizontally is the slip s

4 Verification

The model calculations are based on constant stator frequency, flux and induced voltage consequently. In practical tests the internal voltage cannot be measured, therefore the test conditions are not equivalent. To prevent the influence of harmonics in inverter supply the verifying measurements were done at standard net frequency f = 50Hz. All the theoretical conclusions are in very good agreement with the measured characteristics in Fig.9. There is evident in here much lower value of power factor in generator run, as well as growing stator current value. The stator current curve can remain the circle diagram of AM which is well known to seniors. The value of internal voltage Ui in Fig.9 is not measured, but only calculated from other measured values. Because at constant terminal voltage it is higher in the generator run area, there is here also very high flux and magnetizing current, therefore the power factor is much lower then in simulation with constant Ui.

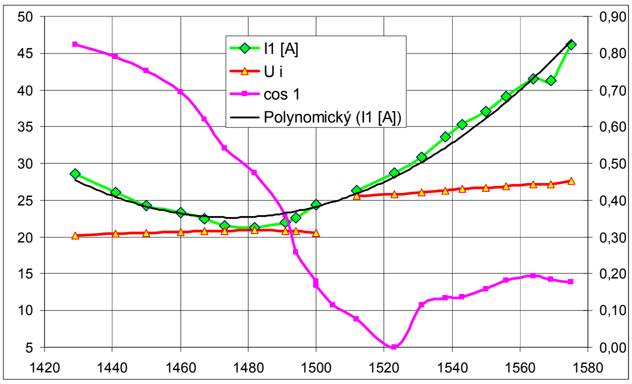

Fig.9 Measured characteristics of stator current I1 and power factor (cosφ), vs. speed (RPM) for AM (1,1kW, 1420 RPM), at supply 50Hz, 23V in motor and generator run. Also the induced voltage Ui is charted.

5 Conclusions

The numerical results show, that the chart in Fig.5 is a bit exaggerated in the stator voltage vector inclination, but the stator current is due to very big reactive component of magnetizing current rotated very significantly and its power factor (cosφ) is consequently very low. In examined machine it does not exceed 0,6 at allowed value of the current (and temperature rise). It can grow also to better values with growing current, but it is out of operational range.

In general the electrical power output of AG is under the rated value of mechanical rated power of this machine in motor run, although its stator is designed on much higher power.

The control of the stator terminals voltage to constant value is not optimal for generator; it brings in the small machines the increase of internal voltage and the flux consequently, which results in the increased stator current and reduced power factor.

With the frequency increase in variable speed generating the voltage drop on the stator leakage reactance should be compensated by slight voltage increase to keep the internal voltage (and flux) on the constant value.

References:

[1] KURKA, O. - BRŠLICA, V.: „The Concept of 3rd Generation Mobile Electrical Power Sources." *Proceedings of ERK'99*, Portarosa, Slovenia, 1999, vol. A, pp. 375 – 378,

[2] BRŠLICA, V.: The Variable Speed Power Generating System Conception. *ELEKTRO 2001*, Žilina, SK, 5/2001, pp. 65-70, ISBN 80-7100-836-2,

[3] BRŠLICA, V. - KURKA, O. - MELICHAR, M.: Optimal rotor for PM generator, *Proceedings of WSEM 2000*, CVUT Prague, CZ Sept. 2000, pp.

[4] KURKA, O. - MELICHAR, M. - DRTIL, J.: Generators for VSCF mobile electrical generating sets, *Proceedings of SME 2003*, Gdansk, Poland, August 2003, pp.

[5] BRŠLICA, V., TINCQ, L.: Variable Speed Asynchronous Generator Optimal Efficiency, in *Proceedings of XI. ISEM 2003*, CVUT Prague, Sept. 2003, pp.155-160

[6] BRŠLICA, V.: Variable Speed Asynchronous Generator, In: *Proceedings of ICREPQ 2004*, Barcelona, 31/3 - 2/4 2004, CD, pp8, PAPER Nº: 4.205, ISBN: 84-607-9889-5

[7] BRŠLICA, V.: Battery Charging from Variable Speed Asynchronous Generator In *WSEAS Transactions on Systems*, Issue 8, Vol. 4, Corfu, Greece, August 2005 pp 1363-1367, ISSN 1109-2777

[8] BRŠLICA, V. - MELICHAR, M.: Mobile electric power sources In Proceedings of reviewed papers SPECIAL TECHNOLOGY 2006, Bratislava Slovak Republic, 4. May 2006, pp88 – 95, ISBN 80-8075-128-5

[9] BRŠLICA, V.: The High Efficiency Low Power Motors, In *WSEAS Transactions on POWER SYSTEMS*. (Issue 10, Volume 1, October 2006, ISSN 1790-5060, pp. 1824 - 1830).

[10] BRŠLICA, V. - MELICHAR, P.: Low voltage battery source with asynchronous generator, In *Proceedings of International conference on low voltage electrical machines LVEM 06*, 13- 14 November 2006, Brno – Šlapanice, CZ, pp 48-55, ISBN 80-214-3159-8

Financial Support of Czech Republic Ministry of Youth and Education, Program No OC169 for COST Action 542, is acknowledged