A Technical and Economic Project Analysis of Asynchronous Technology in Distributed Generation Using Methane Gas From Pig Farms

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ABSTRACT The focus of this paper is to study the asynchronous generator (generator of squirrel-cage induction), as an alternative distributed generation technology, in particular the driving of machines using methane gas from pig farms as their fuel. Pig farming has grown dramatically over recent years. This agro-industrial activity produces huge quantities of methane gas which is released into the atmosphere depleting the ozone layer, in addition to contributing to the greenhouse effect. When the subject is environmental concerns, methane is known to be many times more aggressive than carbon. Since the production of this gas is inherent to the pig farming industry, its effects can be mitigated by using it as fuel in an engine to drive an electricity generator, while adding value to the production chain.

INDEX TERMS Asynchronous technology, economic analysis, distribution system, induction generator, methane gas, technical analysis.

I. INTRODUCTION Electric energy performs a fundamental role in the lives of human beings, which sits alongside other fundamental modern day essentials such as transport, telecommunications, treated water and sewage, which together create an infrastructure that is necessary for incorporating the human being into the current model of development. It is for this reason that themes concerning energy are at the heart of human progress, and hold profound importance as the human race searches for a sustainable future. This requires a holistic and multidisciplinary approach, in a scenario that brings together every dimension of the problem, including from technologies, social economic and environmental policies [1]–[3].

Three-phase induction machines are widely used as motors, producing mechanical force from electric power. This equipment possesses a low weight/power ratio when compared to other machines, as well as present robustness and simple construction concepts, low fabrication costs and do not possess an excitation system, thus no need for changing brushes and as such periods between maintenance are longer [4].

As the demand for electric energy is constantly increasing due to the growth of the population worldwide, when dealing with cost benefit, the induction machine takes center stage as an alternator, due to its small size per generated kWh, thus becoming used at constant speeds, consisting of hydroelectric, thermal, diesel group plants among others.

In light of the recent energy crisis in Brazil, aggravated by prolonged dry periods, reservoirs associated with hydroelectric production have remained low, thus leaving the energy system on a state of alert, and as a consequence has led to the rationing of electric energy. Faced with the aforementioned scenario, the need arises for the implementation of rational and efficient methods in the use and generation of electric energy.

Distributed generation aids in the supply and reliability of electric energy in situations of systemic failure, besides increasing the capacity of network generation.

Through the use of methane gas for the generation of energy, one increases the possibility for the ramification of the energy matrix of the Brazilian electric energy system.
This contributes to decreasing dependency on a hydro based supply, and as such strengthening the homogeneity of distributed generation with alternative supplies, such as methane gas.

The pig industry has seen dramatic growth over recent years, this agro-industrial activity produces enormous amounts of methane gas that when released into the atmosphere attacks the ozone layer, in addition to contributing toward the greenhouse effect, it is well known that methane is more aggressive than carbon dioxide in intensifying this phenomenon. The production of this gas is inherent to this particular economic activity, its use therefore as fuel, in motors for driving an electric energy generator, aids in cancelling such effects, while adding value to the production chain.

In light of the need to strengthen the power network, due to the growing demand in energy consumption, one sees the possibility of power generation via the burning of methane gas from biodigesters. The confined biogas is burnt, thus transforming the methane into carbon dioxide, and through such reducing by as much as ten times its detrimental effects to the environment.

The burning of biogas in motors, driving synchronous electric generators, has already been applied to various sectors of industry. Different to synchronous generators, asynchronous generators have their magnetization provided through the bus itself, aided by a capacitor bank that makes the necessary reactive power circulate between the generator and capacitor bank.

Compared to conventional synchronous generators, the very synchronization process of these small generators, at the moment of reconnection, demands trained individuals to perform the task, otherwise these procedures can interfere in a detrimental manner on the local distribution network.

The asynchronous technology associated with distributed generation provides the means to overcome these difficulties. In a situation of disconnection from the grid, the asynchronous generator demagnetizes, thus stops generating terminal voltage, in this way it becomes an induction generator of the squirrel cage type, which is an ideal candidate for distributed generation due to its operational characteristics.

These environmental and financial advantages are linked to the burning of methane gas, as it can generate clean energy, since it is produced naturally in the productive chain of pig farming. The burning of methane, in this way, avoids the release of the gas, and as such the extremely harmful effects regarding global warming are radically decreased. In fact, the impacts from methane on the environment are many times greater than those of carbon dioxide.

The application of the asynchronous generator to the motor-generator group produces cheaper project implementation costs. This is due to the lower acquisition cost of the three-phase induction generator when faced with that of the synchronous generator.

The expansion of a particular system, in which there already exists the use of biogas, a byproduct of pig farming, the induction generator is also recommended, as well as in the substitution for the loss of working life of the synchronous generator already in operation.

With the growth in the pig herds over recent years across the world and the legal imposition concerning the treatment and destination of waste byproducts in the installation of biodigesters, this study is conducted in accordance with these new laws that incentivize distributed generation. In addition, one needs to consider technical security found in asynchronous technology, and in this regard the present study is highly relevant as to its intelligent use of generators in distributed systems.

In the current literature regarding the squirrel cage induction generator that operates in distributed systems, emphasis is given to:

Studies dealing with power flow, efficiency and performance of the three-phase induction generator connected to power network are presented in [5]–[7]. A study where a comparison is made between the difference of synchronous and induction generators for application in distributed generation is presented in [8], [9]. In [10], a study is presented on short-circuits in induction generators connected to the grid.

There are several published works related to the squirrel cage induction generator connected to the distribution grid at variable speeds [11]–[29], with the use of wind energy, widely used in wind farms.

However, it is necessary to perform the rectification and inversion of the generated current for connection to the distribution grid, making the variable speed squirrel cage generation system relatively expensive. Compared to the use of the constant-speed squirrel cage induction generator, it is technically and economically viable when the induction generator operates directly on the distribution grid, since an inverter is not required for power generation.

A study on distributed generation is proposed in [30], as a hybrid electric system where an induction generator operates with a solar panel. In [31], a hybrid system is presented, connected to a power network onto which the induction generator is connected to a photovoltaic energy system, and the squirrel cage induction generator is driven by a biogas generator. Another similar study, can be found in [32].

In [33], there is a process of decreasing the inrush current during the connection of the squirrel cage induction generator to the distribution grid. An investigation of skew effect is presented by [34], whose work focuses on the steady-state and transient dynamics behavior of the squirrel cage induction generator in the power grid.

Still concerning the connection of the squirrel cage induction generator to the grid, it is shown by [35] the investigation of electromagnetic torque pulses, which can result in problems in turbine couplings and the solution of this problem is presented. Another study on stability when the induction generator is connected to the grid is presented by [15].

According to [36], in order for the squirrel type induction generator to generate electric energy, the induction generator needs elevated reactive energy. The asynchronous machine
of the squirrel cage type is indicated for use as a generator under constant speed, due to the low cost of acquisition of the machine and coupled with its robustness; it can be operated through its connection to the energy distributed network from biogas [37].

In light of the applicability of the squirrel cage induction generator - asynchronous technology, there arises the need for a design, economic and technical viability study of the squirrel cage induction generator in distributed generation that uses methane gas that comes from the pig industry as primary or mechanical power.

Coupled with the advantages of the squirrel-cage induction generator, its use from the power generation by the swine methane gas is also highlighted, contributing to the reduction of environmental impacts and sustainable energy.

Given the bibliographic survey it is noted that there is no study relating the technical, economic and implementation project of the induction generator design from the renewable energy from the burning of methane gas from pig farms.

II. PROJECT RATIONALE

The research performed herein developed an electric energy motor-generator group with its power matrix based on biogas produced by the pig industry. This is based on the premise that this economic activity is strongly established, and through environmental legislation is copiously equipped with biodigesters that are destined to the confinement and burning of biogas, which is a byproduct of the pig industry. Biogas, for which the main component is methane, is very aggressive to the natural environment. Current environmental legislation demands the installation of biodigesters for the confinement and burning of the gas produced, thus vastly decreasing the adverse environmental effects. In this way, the use of methane gas is timely with positive effects for the natural environment when the subject is the generation of electric energy, as one sees a reduction in costs for pig farms, as well as adding higher economic value to the livestock industry.

The Brazilian pig herd has expanded in a significant manner over recent years, with an average annual growth of approximately 8% according to data from the Brazilian Institute of Geography and Statistics/Instituto Brasileiro de Geografia e Estatística (IBGE), reaching in 2011 a number of approximately 39 million head [38]. As in the rest of Brazil, the pig industry in Mato Grosso is growing in a significant fashion, with a herd of approximately 2.1 million head in 2010 [39], and is classified as the state with the highest growth regarding pig production in the country between 2004 and 2012, with growth measured at 171% [40]. With the significant expansion of the pig herd in Mato Grosso over recent years, the legal imposition concerning the treatment and destination of waste associated with these herds has led to, and will continue to lead to, the installation of large biodigesters in the state of Mato Grosso, as well as in other states and regions that have pig industries as previously stated.

Therefore, since the emission of biogas, rich in methane, is an effluent in the production of pigs, there is nothing more efficient than the use of this kind of energy for power generation. Methane gas can be used as a fuel in a motor for driving electric energy generators, and then these can be connected to the distribution network, following the National Electric Energy Agency/Agência Nacional de Energia Elétrica (ANEEL) Normative Resolution (NR) No. 042 and Distribution Procedures/Procedimentos de Distribuição (PRODIST) recommendations. The recent edition of the state decree that waives the charge of Tax on Circulation of Property and Services/Imposto sobre Circulação de Mercadorias e Serviços (ICMS) tax, along with Social Integration Programs/Programas de Integração Social (PIS) and Contribution to Social Security Financing/Contribuição para Financiamento da Seguridade Social (COFINS) by the Federal government, on the production of energy generated by micro and mini distributed generation, are strong motivational factors toward the growth in the demand and use of biogas.

The burning of biogas in motors driving generators for energy production has been used in Mato Grosso for some time; the current capacity of energy production through use of biogas from the pig industry in Mato Grosso (MT) is 17,408.00 MWh per month, which is sufficient for supplying 87,040.00 middle class residences with around 200 kWh per month in consumption [41].

In topics related to asynchronous machines, classic literature has given evidence basically for the concept of induction motors [42]–[44]. This also occurs in a majority of scientific research related to the theme, as the asynchronous machine was designed to operate as a motor, which is contrary to the synchronous machine that is used as a generator in a majority of power plants. The first studies involving the induction generator date back to the 1930’s, with the main advantages, when compared to synchronous generator, being in the acquisition cost that is approximately 40% less for low powers, along with greater robustness, it is simpler and dispenses the need of a synchronous device. The large Brazilian power generating plants and those found around the world use synchronous machines; these are responsible for generating, in addition to active power, the reactive flows necessary for the system. In Brazil, before the ANEEL resolution No 482, the exploration of small energy potentials was limited to studies involving the operation of systems [45].

III. PROJECT DESCRIPTION

This Project deals with the use of methane gas produced in biodigesters from the pig industry, where a 75 kVA transformer station (expandable) is connected to an asynchronous generator of 150 hp driven by a biogas motor.

The project is arranged together with the approval of the concessionaire according to their respective requirements and standards. The last stage of the project is dedicated to elaborating the supply contract and monitoring the electric energy compensation.
This research project integrates the distributed generation access and connection project to the Energisa distribution system (power distribution company), as part of the Research and Development Project entitled “Analysis of Asynchronous Technology in Distributed Generation Using Methane Gas from Pigs.

The research performed herein developed an electric motor-generator group taking as its energy matrix biogas derived from the pig farming industry. This is developed from the premise that this economic activity is strongly established, and through environmental legislation is very well equipped with biodigesters destined to the confinement and burning of biogas, a by-product of the pig farming process. Biogas, for which the main component is the gas methane, is very aggressive to the natural environment. Current environmental legislation demands the installation of biodigesters for the confinement and burning of gas, and as a result significantly decreasing its damaging effects.

The Ordinance Edition 482/ANEEL/2012, which regulates the connection of distributed generation units to distribution networks and establishes “energy compensation”, certainly will motivate evermore installations of electric energy motor-generator groups that use biogas in the generation of electric energy.

The Project has as its goal, the development of an electric energy motor-generator group with biogas as its fuel, and using asynchronous machines as generators. The intention therefore is, through asynchronous technology, mitigate the impacts caused by the connection of small generators on the distribution system, mainly from the point of view of operational simplicity and increased security that asynchronous technology provides to distributed generation.

The design of the connection to the distribution network has as its objective to meet the requirements presented in the Technical Norm/Norma Técnica (NTE)-041-Energisa, for access in medium voltage from an energy generating plant, with power of 110 kW. This setup has a biogas matrix, the by-product of the pig farming industry, by means of the consumer unit number UC15095121, at the property of Nilton José Dal Bem, situated at the rural property denominated “Fazenda Três Passos”, located on the road Morocó, municipality of Sorriso MT.

The consumer unit in question is served by a rural three-phase distribution network of 13.8 kV. It has a primary voltage reading, located at the coordinates: ZIL0627751; UTM8539656. The energy supply contract contemplates a green peak-hour charge rate, with demand contracted of 102 kW. The installations serve the pig and poultry farms. Downstream of the measurement, there are two transformer stations 13.8 kV / 220-127 Volts, 75 kVA. On each transformer station there exists by voltage-ramp reversal, a diesel generator group, destined to serving 100% the demand at peak hours and providing security in the supply in case of a blackout on the part of the concessionaire.

In order to use the biogas available at the property, an experimental central generator will be installed together with the biodigesters. To provide the connection from the experimental generator to the primary network, a three-phase 13.8 kV network 986 meter extension will be built, of the conventional rural type. The motor is from MWM International model G6, 12 T, direct from the manufacturer for operation with biogas, with an exhaust manifold gasket, silent and a battery setup.

The generator is an asynchronous “motor” of make WEG, four poles, star connection, 380 volts, degree of protection IP 23, isolation class H, overheating 80 °C, possesses temperature detectors on the windings and on the bearings, as well as dehumidification resistance. The control function will be performed by the automation system provided for the assembly.

The data and parameters for the induction generator used in the project are presented on Table 1.

The standard NTE-041/Energisa, which deals with technical requirements for the connection of micro and mini generators to the Energisa distribution system, consider in item 8.9, the need for installing shunting equipment, protection and control at the connection point of the central generator. Such devices are listed and specified on Table 2.

All operating operations will be performed through a supervisory automation system, for which the central processor is a programmable logic controller from Shneider mark- CLP Modicon M221 Schneider Eletric. All the electric magnitudes for energy, as well as data for gas consumption, temperature among others, will be constantly monitored, thus producing the subsidy for protection, disconnection and reconnection. Through use of a real-time communication system, via SMS, the operation will be also be supervised remotely.

In order to connect the experimental central generator to the consumer unit, a three-phase extension of the network was constructed of 13.8 kV, 960 meters, which contained a new transformer station of 75 kW (a power factor close to the
induction generator unit). To attain this, it is not necessary to increase the load in the consumer unit, as the reading is primary and situated at the property entrance. In addition, the new 75 kVA transformer station does not contain a connected load, as it serves only as a connection from the central generator to the internal primary distribution network on the property, which does not constitute as a load increase.

This new 75 kVA transformer station is required to connect the 380 V induction generator to the 13.8 kV medium voltage grid. In the consumer unit concerned, the measurement is performed at medium voltage due to the long distances of the loads (iming to supply the three phase loads in the desired places). Thus the measurement is carried out only on the main pole derived from the electric power concessionaire.

Table 3 shows the transformer plate data used to connect the induction generator to the local distribution grid.

The network was designed with reinforced section DT concrete posts, standardized structures PT1, P3-P3 and Transformation Station N3-P. The conductors will be bare aluminum, 2-AWG-CAA gauge. Primary protection and sectioning will be performed by a fused switch. Protection against atmospheric discharge will be provided by a 10 kA, 12 kV distribution lightening conductor. Low voltage general protection will be provided by means of the 200 A thermomagnetic circuit breaker, in accordance with NTE-014-Energisa. The grounding was designed according to the norms NTE-014-Energisa and NBR 5410 - Brazilian Association of Technical Standards/Associação Brasileira de Normas Técnicas (ABNT).

The energy supply contract possesses clauses that predict intervals between alterations of the contractual conditions, especially in terms of the tariff mode and demand limits contracted over periods, considering the seasonal tariff system. As one is dealing with an experimental situation, participation in a project Research and Development/Pesquisa e desenvolvimento (P&D) financed by Energisa, a special tariff regime was requested for the P&D period. The aim here was that the consumer unit would not be penalized due to any small deviations that may occur in light of the experiment performed through the scientific research.

Regarding island operation, there was a doubt before the operation of the researched generator concerning the subject the damping time of the voltage generated, when the asynchronous generator operates with capacitors to compensate for reactive flow, since no conclusive bibliography was found on the subject. A long period in the generated voltage damping, when the induction generator operates connected to a voltage free network; this would lead to the possibility of operational risk of the local network in those moments shortly after network maintenance shutdowns, as occurs in the case of synchronous generators, where this is a permanent risk.

In the tests performed during operation assisted by the asynchronous generator, with operational capacitors, the voltage drop time generated by the machine, when the network is de-energized, the demagnetization process takes approximately 5 seconds. This result supports the theory of greater safety of asynchronous generators for Distributed Generation compared to synchronous generators.

Therefore, the asynchronous generator relinquishes the need for anti-islanding protection, as in its constructive nature, sees that no voltage is generated while islanding, inclusive with capacitors present.

There is no need for protection against variations as the voltage on the generator terminals is that present on the local distribution network. There exists the need for protection against reverse power, as in the case of power failure in the primary machine, the generator will go on to operate as a motor, with positive slip and will drain power from the mains and powering the primary machine.

The simplicity in construction, robustness, production in series for the wider motor market, established network maintenance, easily available pieces for reposition, all these aspects go on to make the asynchronous generator (induction motor) a machine of lower cost than synchronous generators, mainly in the micro power range of distributed generation.

Taking into consideration the operational facilities, the induction generator does not need synchronism or

| Protection Requirement                   | Installed Power until 75 kW | Maximum time engaged |
|------------------------------------------|-----------------------------|----------------------|
| Undervoltage Protection (27)             | 0.8 p.u.                    | 5 sec                |
| Overvoltage Protection (59)              | 1.1 p.u.                    | 5 sec                |
| Under frequency Protection (81U)         | 59.5 Hz                     | 5 sec                |
| Over frequency Protection (81O)          | 60.5 Hz                     | 5 sec                |
| Overcurrent protection (50/51)           | As per power input standard | N/A                  |
| Sync relay (25)                          | 10° 10% Voltage 0.3 Hz      | N/A                  |
| Anti-islanding                           | N/A                         |                      |

| Data                        | Value     |
|-----------------------------|-----------|
| Nominal Power               | 75 [kVA]  |
| Primary rated voltage       | 13800[V]  |
| Secondary rated voltage     | 380 [V]   |
| Primary rated current       | 3.14 [A]  |
| Secondary rated current     | 113.95 [A]|
| Primary/secondary connection| Yg/Yg     |
| Phases                      | 3         |
| Yield                       | 0.983     |
| Frequency                   | 60 [Hz]   |
voltage adjustment procedures, which makes the asynchronous generator a much simpler generator than the synchronous machine.

With the continued operation of the generator set possessing a supervisory and data transmission system envisages the possibility of integration of some new data capture. This will allow for a new stage of research, such as obtaining information on the control of hydrogen sulfide levels in the fuel (biogas), through the installation of an oxidation and coal filtration system, in two moments, with remote monitoring using a previously installed supervisory system.

Therefore, comparing the power performance and the performance of the set, without the filtering of H₂S, the gas present in the biogas is detrimental to the burning process. The innovation sought in this study is the development of an efficient filter for reducing the hydrogen sulphide indices in biogas, which results in higher efficiency in energy generation, along with greater durability of the combustion machine.

IV. DESCRIPTION OF INSTALLATIONS

In order to study the asynchronous generator driven by a biogas motor, a special generator motor group was designed, composed of a six cylinder diesel motor of 289 hp, factory modified to operate in Otto cycle and produce 160 hp through the burning of biogas. The motor utilized is the MWM, model G6-12T. The asynchronous generator utilized was an asynchronous machine WEG 150 hp – 110 kW.

The generator motor group was installed on a pig farm in the municipality of Sorriso/MT, which made its biodigesters and biogas available for performing the research.

The farm counts on a consumer unit served with primary voltage by a three-phase rural network of 13.8 kV, with primary metering based on the green tariff modality and with demand of 102 kW.

To connect the experimental unit to the electric system of the farm, a primary network extension was constructed and a three-phase transformer of star/star connection was installed with a secondary voltage of 380 volts. The original proposal was to connect the generator in low voltage, but the distance between the biodigester and the transformer on the property did not permit the transport of energy in low voltage or the transport of biogas through pipelines. Figure 1 shows a view of the installed experimental central generator.

Figure 2 shows the housing for the experimental plant, in “A”, a lung vessel is shown that was developed by the project team to stabilize the pressure and input release of biogas into the motor. In “B”, a hydrogen sulphide retention filter is shown, also developed by the team, which improves the quality of the gas injected in the engine, due to the harmful properties of H₂S, which causes engine damage and reduced power output.

The efficiency of the filter still has not been studied, as a larger study series will be necessary for obtaining conclusive data. The intention thus is to continue collecting data through the data acquisition and remote automation system installed in the experiment.

The biodigester shown in Figure 3, indicated by the letter (A), plays the role of confining the methane rich biogas, this gas is extremely harmful to the natural environment, as it contributes to the increase in global warming. This biogas confined in the biodigesters is burnt in flares, these are indicated for transforming methane into carbon dioxide, thus reducing many times over the damaging effects to the environment.

The motor generator group, indicated by Figure 4, is equipped with the connection to the asynchronous generator, exhaustive tests and operations were performed that stored data collected by an energy analyzer and by the automated supervisory systems installed onto the generator unit.

The production of internal combustion motors for burning methane gas is already a reality in Brazil. However, manufacturers currently on the market offer motor-generator
groups that only use synchronous machines. As previously mentioned, this Project developed a motor-generator group to operate with methane gas, while using asynchronous generators.

The first advantage of the proposed innovation is the reduction in the cost of the equipment, as the asynchronous generator is in fact nothing more than normal induction motor. These generators are widely available on the market at a kW cost that is much lower than the synchronous generator.

Another important factor that contributes toward reducing further still the costs in asynchronous generation is there do not exist any excitation systems, speed regulation or synchronization with the electric network, as is demanded in synchronous generation. One also needs to consider the question of security in operating the induction generator when connected to the distribution system. The fact that its excitation is produced by the network, in cases of shutdown, in a few seconds there will be no improper supply from the asynchronous unit. The equation of the three-phase squirrel cage induction machine in the domain $dq0$, is given in [47].

\[ Q_{\text{biogas}} = N_c \cdot E_t \cdot P_b \cdot t \]

where,
- $N_c$ - Number of head in herd;
- $E_t$ - Total manure [kg manure];
- $P_b$ - Biogas production [kg biogas/kg manure];
- $t$ - Time [day];

Considering that,
- $E_t = \text{total manure} = 2.25 \text{kg manure} / \text{(day pig)}$ - agreement with model (CENBIO) [50]; and
- $P_b = \text{Production of Biogas}$ (is equal to 0.062 kg biogas/kg manure equivalent to 0.086 m$^3$ biogas / kg manure) - obtained experimentally by [50].
TABLE 6. Energy potential by quantity of pigs. Source: Own authorship.

| Pig Head | Methane (m³) | Energy potential (kW) |
|----------|--------------|-----------------------|
| 500      | 4.03         | 5.75                  |
| 1000     | 8.06         | 11.51                 |
| 4000     | 32.25        | 46.05                 |
| 8500     | 68.53        | 97.86                 |
| 9000     | 72.56        | 103.61                |
| 85000    | 685.31       | 978.62                |

Table 6 shows the relationship of pig heads with the amount of m³ of methane gas produced in relation to the electrical power.

For the purpose of calculation, the concentration of methane in biogas at 60% will be considered - average concentration obtained from measurements in biodigesters.

The calorific value of a fuel represents the amount of energy in the material. The calorific value of biogas will vary according to its composition and can be calculated, however in cases where the exact composition is not known, reference values can be used, as shown in Table 6.

Table 7 shows the variations in the calorific value according to the percentage of methane (CH₄) in the biogas in accordance with [51].

Also according to [52], the calorific power of methane with 60% CP concentration is 17,706.70 kJ / Kg = 5,100 kCal/m³ = 5.91 kWh/m³.

With biogas flow data, power, operating regime (DG- Distributed Generation), the generator must be selected to identify the total generator power and the efficiency or conversion factor. Table 8 shows the rate of energy conversion from gas to electricity with the ratio of the biogas combustion engine and the induction generator. This Table was created from data in manufacturers’ catalogs (ER-BR, Leão Energia, Fockink and CHP Brasil) and monitoring of the demonstration units monitored by CIBiogás-ER.

From the biogas flow obtained experimentally of 65 m³/h, Table 8 in bold is highlighted the relationship to be used in the generated energy calculations.

To estimate the daily value of electricity production, considering the standard calorific value, equations (2) and (3) can be used.

\[ E_p = V_{dv} \cdot F_{cf} \]  
\[ E_p = \eta \cdot \frac{V_{dv} \cdot CP}{100} \]  

\[ V_{dv} = Q_{biogas} = 65 \text{ m}^3/\text{h} = 1560 \text{ m}^3/\text{day} - consumed \text{ by \ the \ generator - farm data.} \]

Due to the flow, the maximum power of the machine will be 108 kW according to Table 8. Soon, \[ P = 108 \text{ kW} \]

\[ \eta \text{ (%) income from distributed generation} = 22.8\% \]

\[ P_{max} = 0.8 \cdot 108 = 86.4 \text{ kW} \]

The conversion factor (kWh/m³) provided by the manufacturer according to Table 8 is CP = 1.35.

Generation estimate for the chosen induction generator set.

Applying equation (2), it is obtained:

\[ E_p = V_{dv} \cdot F_{cf} = 1560 \cdot (0.8) \cdot 1.35 = 1,684.8 \text{ kWh - operating 80\% of the day.} \]

According to the data calculated from Table 7, the value of 5.91 kWh/m³ is found, therefore applying in equation (3):

\[ E_p = \eta \cdot \frac{V_{dv} \cdot CP}{100} = 22.80\% \cdot (1560 \cdot 0.8) \cdot 5.91) / 100 = 1681.6 \text{ kWh - operating 80\% of the day.} \]

As shown in the application of equations (2) and (3), the values kWh are close. This value is very close to the value used in the economic feasibility study. Note that the flow was rounded to 65 m³/h, which makes the result close to the 1,689.6 kWh presented in the economic feasibility.

Therefore, the estimate for the production of biogas in the state of Mato Grosso will be approximately 12,190,500.00m³ of biogas per month, when considering the above stated from a state of the art point of view. The ratio of 1m³ of biogas to electricity is 1,428kWh, as previously calculated and also presented by [53]. Thus the generation of biogas in the state of Mato Grosso has the potential to generate 17,408.00MWh per month, which is sufficient to supply 87,040.00 middle class residencies with an average consumption of around 200 kWh per month [41].
The use of tested technology in this study has demonstrated the viability of using this type of energy. Other states in Brazil, such as Paraná and Santa Catarina, possess pig herds even larger than those of Mato Grosso, in a way that the reporting of results can produce expressive numbers for the use of biogas in the generation of electric energy.

The security offered by the asynchronous generator through not refeeding distribution networks during shutdowns, allied with operational simplicity and maintenance, as well as the low costs of installation, can suggest to electric energy distribution companies the insertion into their technical norms the use of induction generators. This would be the case especially for the connection of small generators to their networks, removing as such the worry of improper refeeding by the operation of island generators.

VI. SOCIAL-ENVIRONMENTAL RELEVANCE

According to [54] developed countries increased energy consumption in less than 100% over 20 years, during the same period South Korea increased its demand by 306%, India by 240%, China by 192% and Brazil by 88%, as such any attempt at social inclusion will cause additional pressure on energy consumption.

When considering socioeconomic and environmental development, it becomes evidently clear that one needs to consider the incorporation of bioenergy, energy of the type arising from agricultural and forest products and by renewable sources such as hydroelectric, wind, solar, geothermal and ocean energy. Energy sustainability with social gain cannot depress any source of energy generation, as only the sum of all available sources can produce the energy necessary for a permanent social inclusion of the population in Brazil.

The first comparative advantage of the electricity generation system using biogas that originates from pig waste comes from the possibility of incorporating new renewable energy sources without competing with food agriculture, as is the case with ethanol, which is an additional value, besides its removal of methane from the atmosphere.

The second comparative advantage stems from the possibility of multiple production points that during the year, if well-coordinated throughout the production period, may have continuity of energy production, unlike the “productive windows” which are periods with reasonable risks to the main crop, when compared to energy obtainable from crops, such as sugarcane.

The third advantage is found in the extension and the geographic location of the state of Mato Grosso, which in greater part is situated in tropical zones. Therefore, the elements necessary for the production of pigs are of easy access, thus widening the use of locally produced products. This, in turn, can guarantee the permanence of this agribusiness in a constant productive state with lower cost. The state of Mato Grosso also possesses a lush biodiversity, which provides various options when considering elements for the sustainability of pig production.

This project brought with it a measurable gain to the agricultural producer, which decreased the production cost through aggregating energy production, thus making the industry more attractive. This is in addition to an indirect gain, which is to demonstrate to society a productive process focused on a relevant environmental concern.

The relevance of the technology employed in this development project meets the acceleration of the change necessary in the production and diversification of Brazilian energy. These innovations, through their energy increase, result in environmental and economic benefits, along with contributing to the economic viability of this renewable energy source and leading to scale gains and long-term cost savings. The number of interested investors is also increased when it comes to long-term contracts for the supply of fuel, as electric energy is an important component that adds cost to the livestock and agricultural industry. Therefore, making the generation of energy from methane biogas within the property an attractive proposition.

VII. ECONOMIC RELEVANCE

The use of asynchronous technology, should that be for reducing costs compared to conventional technology, operational simplicity, network safety and other advantages demonstrated through this project will contribute to the connection of new units using biogas, which today is burnt off with flares. The abovementioned advantages were in fact seen in the region where the experiment was performed, through the heightened interest that the project produced among the small neighboring pig producers. Therefore, the authors herein can affirm that economic gains exist for the rural producer, thus adding value to the pig farming business.

The statement can also be made, through observation at the location of the experiment, that there was a real environmental gain. The properties that own pig production facilities have through legislation the means to explore gas using biodigesters installed for the burning of biogas. Immersed in the reality of the burning of biogas for energy generation as an economic gain, there naturally exists an increased worry concerning the efficiency of biodigesters in a way that maximizes the confinement of the biogas and directing it for burning in motors, thus avoiding the release of the gas into the atmosphere.

Another economic future is the possibility of exploring biogas energy through associations made up of small and medium pig farmers. The model proposed through this project is the vertical concentration of power generation in a micro-region. This consists of a generation plant with large biodigesters and diverse asynchronous motor-generator groups brought together in the most centralized location possible.

The waste arising from the activity at each property, instead of being treated on site will be transported through tank trucks to the plant, where the treatment and extraction of its energy and production of other by-
products will take place. The advantage of the centralized model is in the professionalization of the business, maintenance efficiency and maximization of results by the scale of energy production and by-products from this process.

VIII. ECONOMIC VIABILITY

The economic viability study took as its base data from the implementation of the project and energy generated, while considering income based on energy compensation in the normative resolution 482/ANEEL/2012. Return is demonstrated on a five-year horizon. A discount rate was considered at 13.74% per annum, which resulted in a 29 month payback. The study took as its basis the cost of equipment and installations undertaken in the project.

Costs not associated to the acquisition and installation of equipment directly linked to the generator unit were not considered, as in the cost with acquisition and transmission of data, remote automation and other scientific costs not directly related to the generating unit.

Another adopted scenario considers the energy generated by 80% of the installed capacity at 80% of the time. This was the scenario considered as real, keeping in mind maintenance stops and variations in the production of biogas. In a more optimistic scenario, payback can be reduced into a few months. In the worst-case scenario imagined, payback increases to 36 months.

The payback is taken as the sum of the IRR and the current discount rate $\frac{13.74% + 34%}{2} = \text{approximately 48%}$. Chronologically considering 60 months (5 years) as 100%, the value of 48% in equivalent months, results in a payback

FIGURE 5. Economic cash flow forecast.

FIGURE 6. Forecast profits; (a) Accumulated profit or loss; (b) Profit and loss.
TABLE 9. Projected financial scenario.

| Return Indicators          | Value          |
|----------------------------|----------------|
| Current discount rate      | 13.74%         |
| NPV (Net present value)    | R$ 155,263.43  |
| IRR (Internal Rate of Return) | 34%            |
| Payback (profit return)    | 29 months      |
| Initial investment         | R$ 260,370.00  |

of 29 months. The data for this economic viability study is presented on Table 9.

Internal rate of return was admitted at 34% per year for the payment of the gross investment. The current discount rate is obtained from the discount rate on gross revenue to obtain net profit (fixed cost plus depreciation), considering an average of 5 years or 60 months.

Regarding the electricity generated, the following results are presented:

- Generated power = 80% \times \text{installed power} = 0.8 \times 110 \text{ kW} = 88\text{kW}
- Hours worked per day of operation = 80\% \times 24 = 19.2 \text{ hours}
- Energy generated / day = 88 \times 19.2 = 1,689.6 \text{ kWh}
- Energy generated / month = 1,689.6 \times 30 = 50,688 \text{ kWh}
- Energy generated / year = 50,688 \times 12 = 608,256 \text{ kWh}

Based on the investment values, it was possible to carry out a preliminary analysis of economic viability, considering a 5-year planning horizon due to the depreciation of equipment. The cost shown is based on the average value of electricity in the rural area, of R $ 0.2594 / kWh.

**Calculation of gross revenue (generated) = 60.8256 \times 0.2594 / \text{kWh} = R$ 157,593.60**

From these calculations, Table 10 is shown to explain the economic viability.

Regarding the variables in accounting for economic viability, it is presented:

- Considering the average percentage of profitability, a current discount rate of 13.74% (approximately 14% over 5 years) was obtained;
- In the first year, gross revenue is R$ 91,929.60 referring to 7 months of operation and 5 months of system implementation;
- The initial investment includes the acquisition and installation of the motor-generator set, the 75 kVA transformer station and the 960 meter network extension. Also included are the projects and the entire legal procedure with the concessionaire - R$ 260,370.00;
- Taxes: Tax discounting was not considered, since the ICMS, PIS and CONFINS do not apply to the energy generated. The surplus generated can be discounted on the next invoice or written off in the account of a consumer unit under the responsibility of the principal holder;
- Variable costs: It was considered zero, because in the period of 5 years there will be no investment in new installation or replacement of equipment;
- Gross profit: Only gross revenue from generation without discounts;
- Fixed costs: Preventive electromechanical maintenance and possible corrective maintenance over 5 years are being considered. These values were provided by the generator set manufacturer contemplating material and execution labor being signed by a maintenance contract. Over the years, the maintenance cost increases due to the natural depreciation of the equipment.
- Depreciation: Value provided by the manufacturer, governed by the market. This value reflects the natural wear of the generator motor set;
- Free profit = Liquid profit.
- Profitability percentage: includes the percentage of profitability between the gross revenue generated and the free profit obtained.

Through the projections of the project at hand, one can represent over a period of 5 years the profit cash flow forecast.
TABLE 10. Project projections.

|                | Year 1               | Year 2               | Year 3               | Year 4               | Year 5               | Total              |
|----------------|----------------------|----------------------|----------------------|----------------------|----------------------|--------------------|
| Gross revenue  | R$91,929,60          | R$157,593,60         | R$157,593,60         | R$157,593,60         | R$157,593,60         | R$722,304,00      |
| Taxes          | R$0,00               | R$0,00               | R$0,00               | R$0,00               | R$0,00               | R$0,00            |
| Variable costs | R$0,00               | R$0,00               | R$0,00               | R$0,00               | R$0,00               | R$0,00            |
| Gross profit   | R$91,929,60          | R$157,593,60         | R$157,593,60         | R$157,593,60         | R$157,593,60         | R$722,304,00      |
| Fixed costs    | R$3,022,50           | R$6,321,83           | R$6,709,76           | R$7,121,49           | R$7,558,49           | R$30,734,07       |
| Depreciation   | R$14,685,90          | R$14,685,90          | R$14,685,90          | R$14,685,90          | R$14,685,90          | R$73,429,50       |
| Free profit    | R$74,221,20          | R$136,585,87         | R$136,197,94         | R$135,786,21         | R$135,349,21         | R$618,140,43      |
| Profitability percentage | 80.74% | 86.67% | 86.42% | 86.16% | 85.88% | 85.58% |
| Discount considered annual | 19.26% | 13.330% | 13.576% | 13.838% | 14.115% | 14.421% |
| Current discount rate | 13.74% |

on bar graphs, which are indicated through Figures 5 and 6. Figure 5 is plotted from gross revenue, fixed costs and free profit, shown in Table 10. Figure 6(a) demonstrates the accumulated profit or loss, while Figure 6(b), only profit or loss. Note that in Figure 6(a) the accumulated profit or loss is obtained from the initial cost of R$ 260,370.00 less the free profit for each year. In Figure 6(b) the free profit for each year is plotted.

Figure 7 shows the EBITDA contribution, which means “earnings before interest, taxes, depreciation and amortization”. This graph shows the difference between gross revenue less fixed cost. After the second year, the values are different, since the fixed cost varies from year to year.

The graph for the margin of contribution vs. fixed costs of the project is illustrated in Figure 8. Figure 8 is plotted from gross revenue and fixed, shown in Table 10.

IX. CONCLUSION

The first advantage to the generation of electric energy using biogas is the added value brought to the business without competing with food agriculture, while eliminating methane from the atmosphere. The second advantage comes from the possibility of creating multiple points of production, thus establishing the constant supply of gas. The third advantage is found in the extension and geography of Brazil which is favorable to pig production and farming. This project brought to the agricultural farmer a gain, making the business more attractive, as well as show to society a productive process oriented toward present day environmental concerns.

The concept put forward in this project was that the use of the asynchronous generator not only lowers implementation costs when compared to the synchronous generator but has an operational simplicity, which favors this machine in distributed generation due to its demagnetization during a blackout from the electric network. This is in stark contrast to that which occurs on traditional synchronous generators.

Biomass residual generated during the livestock production process, points to a business and income opportunity. Biogas produced in the anaerobic decomposition process of organic matter, can be applied to the generation of electric energy. The modeling presented herein was performed from market data and compatible electric energy generation parameters.

Some reference values concerning biogas are estimated and as such are open to variations. Its calorific value and the amount available also varied, which depend on biodigester management, the presence of contaminants, temperature variation, volume of waste and pig breeding cycle among others.

The total investment cost of this project involved the acquisition of equipment and installations (electric and civil) at a cost of R$260,370.00, while not considering the equipment for the acquisition and transmission of data, remote automation and other scientific costs not directly related to the generator unit. The scenario adopted herein considers the energy generated by 80% of the installed capacity in 80% of the time, keeping in mind maintenance stops, production variations, along with calorific variations of the biogas.

The economic benefits were demonstrated by means of an economic viability study with expected return evaluations over the initial investment. The study took as its base data from the implementation of the project and energy generated.

The study was based on project implementation data and generated energy, considering the revenue based on energy compensation by normative resolution 482/ANEEL/2012. The revenue estimate for the rural area considered was of R$0.34 kWh for electric energy production. The return is demonstrated along a financial horizon of 5 years. A discount rate in the order of 14% per annum was also considered.

In the costs per generated unit, the hours stopped were considered (20%), cost of maintenance, depreciation of equipment, and an interest rate of 6.5% per annum. The result is a payback time of 29 months. In an optimistic scenario, the payback can be reduced to a few months. However, in the
worst-case scenario, defined as critical, the payback is extended to 36 months.

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