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HYBRID GAS TURBINE (GT) MECH DRIVE FROM BHGE

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ABSTRACT

This paper describes the advantages, here below summarized, of a GT and an electrical reversible machine that operate in combination:

- Power increase without flange to flange and additional emissions impacts.
- Use of the electric energy, i.e. from renewable sources, reducing fuel and consequently emissions.
- Use the electric energy to improve the life of the GT components.

Since the VFD and motor are reversible systems, they can operate as generator too. This function can be used when the driven compressor load is lower than GT nominal power, reinjecting into the electrical network all the power excess. In this way, the gas turbine can run at the perfect condition to maximize its efficiency and reducing the impact on the emission too. In addition, the electric power can be used to feed electricity to the compression station for opex reduction, for example by the shutdown of the electric station generator or by keeping the compressor station powered in the case of a grid fault that is a typical situation in remote locations where the grid is often unreliable. Also, an advantage in terms of the maintenance life extension can be obtained by the application of this hybrid system.

All possible solutions are tailored on the operator needs.

INTRODUCTION

The BHGE Gas Turbine hybridization concept is applicable to mechanical drive application on new units or as upgrade on existing trains. It leverages the wide range capability synergy that the GT and the Variable Frequency Drive (VFD) electric motor can offer as reversible machine.

The electrical machine depending on how it is controlled can supply power to the mechanical drive train working as helper or can absorb power from the gas turbine working as a generator.

Please refer to the following scheme:

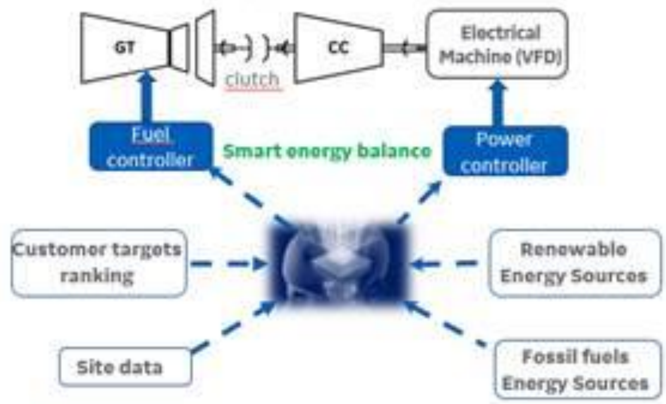

Figure 1 Energy balance scheme

This architecture fits to operators multi-scenarios needs, listed here after:

1- The integration of the renewable energy sources together with the Oil&Gas process.
2- The increase of the process production without impacts on the Gas Turbine and emissions.
3- The independence of the compression Station electrical grid in case of remote locations where there are weak infrastructures.
4- The capability to reduce OPEX costs by stretching maintenance and self-producing electric energy
5- The station availability increase in full electric mode

Since the above scenarios could coexist in the same plant, there's the need of a smart energy balance software that matches with targets properly ranked by remote or local operator.

Moreover, the application of the hybrid system is designed to avoid affect the process set point and his flexibility should assure an optimized management of the compressor station.

BENEFITS OF THE HYBRID CONFIGURATION

This hybrid layout configuration, set up by the GT and the electric machine, allows reach a wide range of operator requests in terms of:

- The power increase & emissions
- The maintenance life extension & opex reduction
- The integration with renewable & energy storage.

In Figure 2 the two different operation modes of this Hybrid configuration are detailed:

- Pure Power
- Power & Life.

When the machine operates in the field of Pure Power no impacts on the maintenance plan occur. In this configuration the helper motor provides extra power ("Δ" in Figure 2 below) to the nominal one of the GT without impacts on the Combustion and Hot Gas Path components and without increasing the emissions, leading the operator to have advantage in terms of production.

Otherwise, when the machine operates in the Power and Life mode, the advantage could be double because the additional power supplied by the electric motor allows have an extra power while the GT operates at partial load. This kind of GT operation, corresponding to a reduction of firing temperature, decreases the life consumption of the combustion and hot gas path components affected by failure mode like thermal fatigue, creep, oxidation, hot corrosion (in H_2S environment) etc...

In this last operating mode the operator's advantage is evident in terms of the maintenance plan extension and availability of the unit.

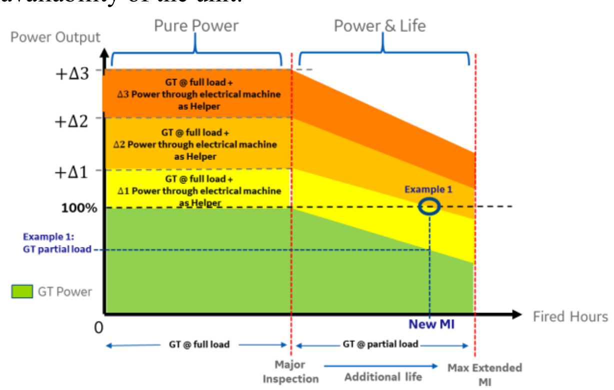

Figure 2 Power augmentation and life extension synergy

As further improvement for opex reduction, the electric power produced in generator mode can be used to feed electricity to the compression station and, hence, it is possible to shut down the electric station generator.

This combination between the GT and the EM allows also integrate the renewable energy with the O&G process by energizing the EM and leading the GT run at partial load with the consequence of reducing the fuel, or running in zero emission mode.

This last option can also be used as an energy storage in pipeline application, in fact it will be possible to accumulate energy as pressure and reduce the fired hours and starts.

THE LNG EXPERIENCE

In the past years synergy between gas turbine with an external helper/generator system has been already successfully carried out by the adoption of an electric motor or a steam turbine, with several references over different size and GT models. Here after the typical layouts of the electric motor option:

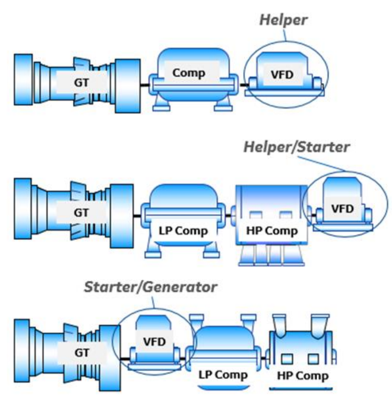

Figure 3 Layout options when VFD is used in LNG refrigeration GT driven trains

In the LNG plants the adoption of the electric motor, VFD type, was used to help the GT to recover the power gap between power absorbed by the compressor and the GT capability over a wide range of environment air temperature and year seasons, in some other cases for the same purpose also steam turbine has been used.

In other LNG applications, the surplus of the power is converted, through the electrical system running as generator, into the electrical power available to the plant.

In this case the electrical machine will run as generator instead of as motor. For each system the transition between helper and generator operation mode is smooth and happens simply by adjusting the torque set-point from positive to negative value with no need of shutdown or open /close switching actions.

The GT main configurations adopted in the past were several and the VFD was mainly used as helper, while in only few cases was used as starter and generator.

The configuration proposed shows some main differences:

- Helper and Generator modes are introduced on the same shaft giving to the operator a full flexibility
- A self-synchronized clutch is placed between gas turbine and centrifugal compressor to run the centrifugal compressor in full electric mode (Zero Emission running)
- Extended helper operation mode not for a process production goal but to stretch the maintenance intervals
- Introduction of "Smart Energy Balance" software to optimize Customer needs and Renewable Energy Sources usage
- Enlarge the hybrid concept to the two-shaft GT's equipped with NGV (Nozzle Guide Vanes)

In Figure 4 it is possible to see the ambient temperature impact on the power output, this because of the air density variation.

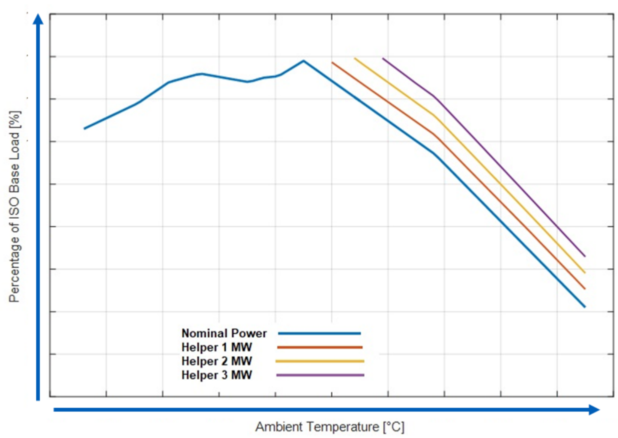

Figure 4 GT Power Output vs Ambient Temperature

To achieve the required power target without introducing any restrictions on process, the helper must match with the compressor speed. As a matter of fact, it is advised to avoid the adoption of a reduction gear for the power transmission between the gas turbine and the electric motor due to the efficiency loss and reliability decrease introduced by such an equipment, so to achieve the desired compressor set point the adoption of an high speed electrical motor is mandatory together with a Variable Frequency Driver technology that is suitable for this purpose. In addition, the VFD allows a wide flexibility in the operability range of the electrical machine, also it is possible, for the electrical machine, to follow the compressor speed that is variable because it is driven by the process demand.

A VFD system is typically equipped by an input transformer used to adjust the electrical network voltage to the motor needs and by a Variable Frequency Converter able to pick up the fixed network frequency from the input side and create a variable frequency output wave to spin the motor at the desired operating point. In the whole operating speed range, the VFD system can provide the nominal torque to the motor, supporting the GT and Centrifugal Compressor needs according to the GT/CC control panel request (i.e. speed or torque set point).

This flexibility allows control the train in speed or in torque mode in order to match the following equation:

$$P=c*n \quad (1)$$

where P=power; c=torque and n= RPM.

The power range of the VFD is from few MW up to 30 MW with single drive thread; higher power is achievable by more than one VFD running in parallel.

In figure 5 a VFD system is shown

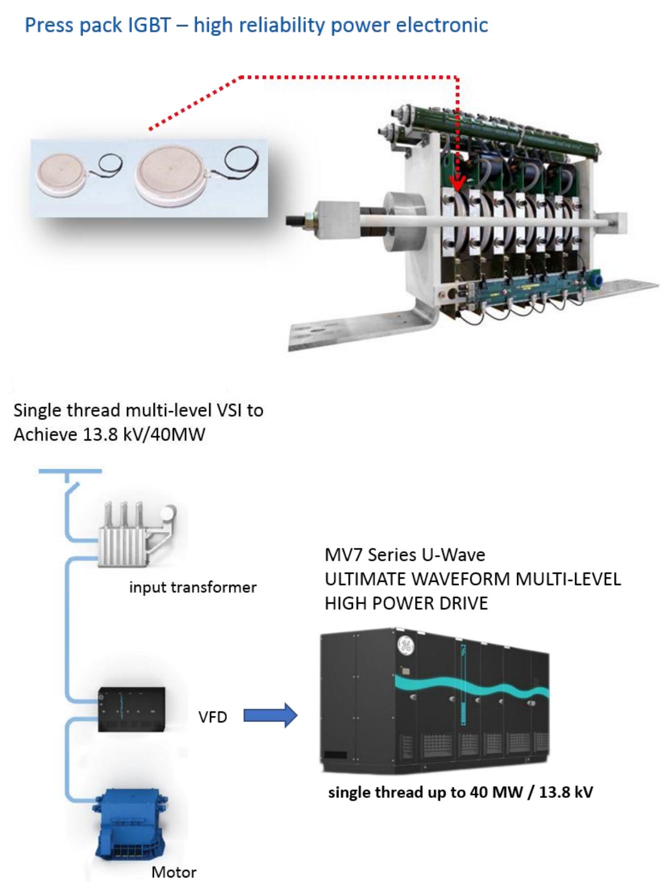

Figure 5 VFD modules

As mentioned before several electrical machine configurations have been used as a function of the application: starter & helper or starter & generator, anyhow the electrical machine has been always put on the compressor driven side, in both cases with either single or double shaft gas turbine. The choice between helper and generator mode is mainly relating to the GT capacity, so the helper mode is used when GT power capacity is lower than the compressor need, while the generator mode is used when the GT power output capacity is higher than compressor absorbed power and these two functions have been already adopted in many mechanical drive trains.

TWO NEW LAYOUT CONFIGURATIONS

Based on our experience we have expanded the application on other gas turbine models but with a new configuration and a better value proposition.

Possible configurations depend on gas turbine model type (Heavy duty or Aero derivative), electrical power machine and operator needs. The implementation of this kind of asset requires engineering detailed verification on shaft line, operability considerations, bearing and other impacted components design for customized solutions.

Two possible layouts could be implemented:

- HP shaft hybrid
- LP shaft hybrid

Hp shaft hybrid… patent pending number WO2014102127 A1

This layout is applicable only for the GT two shafts heavy duty configuration. The allowable electrical power range depends on the GT model: for a Frame 5 can vary between 0,5 and 3 MW.

The above system can operate as:

- Starter/turning
- Helper
- Generator

On this layout configuration the electrical machine is connected directly on the axial compressor shaft, the “cold side”, and replaces the standard starting equipment such as starting motor, torque converter and clutch.

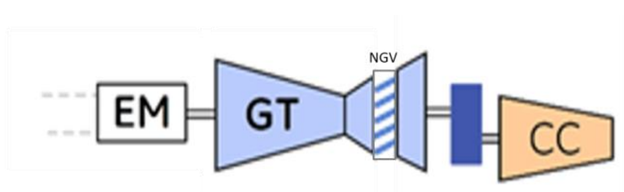

Figure 6 HP shaft hybrid configuration

The mechanical connection of the EM with the gas turbine is direct, and this means that the speed of the axial compressor is the same of the EM. The auxiliary gear box, used to drive the auxiliaries such as lube and hydraulic oil pumps, can be kept or removed according to the level of electrical machine power required. For example on the gas turbine model MS 5002 in case of the adoption of 1 MW electrical machine it is not necessary to eliminate or modify the above mentioned gear box, while in case of higher electrical power it will be required to change or eliminate it. In this case, with the auxiliary gearbox elimination, the auxiliary lube oil pumps must be changed from mechanical driven type into electric motor driven type, while for the hydraulic oil pump it is possible to replace this system by adopting electric actuators. Even if this type of configuration has some limitations in terms of power, the integration of the system within the gas turbine package gives a huge advantage in terms of limited field modification in case of upgrade and on the accessibility of the compressor during maintenance. Since the combination of the gas turbine model type and auxiliaries arrangement are several, a customized solution is necessary to satisfy the project requirements.

Regarding the electrical machine this must be adapted to fit to the available room and cooling requirements.

This need has led to modify the standard cooling system of the motor; here below you can find the new arrangement with the new open air loop. Double fans, equipped with one dedicated filtering system each, are foreseen to allow a 100% full redundancy on the cooling system.

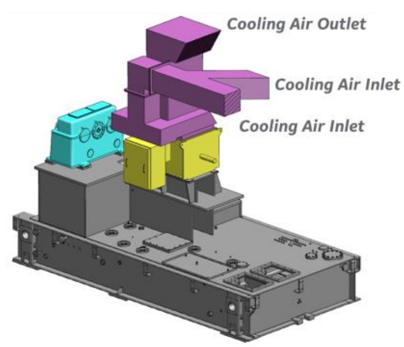

Figure 7 EM air cooling system

This cooling system is configured to allow the electrical machine continuous running even if it is de-energized during off mode, or in all operating speed range condition and with the VFD in failure condition too.

In fact, also the possibility of the VFD failure has been taken into consideration to guarantee high level of availability, so it has been designed to allow the maintenance while the motor is running as free wheel (a typical MTTR is 4 hours, with spare parts available).

In addition, the new systems based on the VFD will have a starting reliability higher than the standard system.

This difference is mainly driven by the simplicity of the new systems vs standard starting equipment, this thanks to the absence of the torque converter and the clutch that are not necessary anymore.

Another aspect that has been taken into consideration in the design of the system is the reliability and maintenance aspects that must be in accordance to the GT typical needs in order to avoid introduce any constrains or bottlenecks: for this reason the electrical machine bearing has been modified and adapted to the GT system.

Moreover, the adoption of the VFD allows the cooldown at higher speed, also called "Fast cooldown" and this will lead to the reduction of 50% of the whole cooldown time; currently this feature is under development at conceptual stage.

The electrical machine can act as a starter, helper and generator as described here below.

<u>Starter operating mode</u>

The electrical machine will be energized after the start command and will bring the axial compressor shaft at the purge speed, after purge time the gas turbine will be fired and starts the warm up sequence. After warm up the acceleration ramp will occur until the gas turbine reaches the self-sustaining speed. As this condition is achieved the starting support is not more necessary and the electrical machine can be de-energized. During the starting sequence the VFD modulates the speed/torque to perfectly match the optimum firing conditions and acceleration ramp. At the end of the startup sequence the electrical machine can run in de-energized mode without any limitations.

Once the gas turbine is started the HP shaft run at its operating speed that can be fixed or variable, the difference depends upon the gas turbine configuration such as simple cycle, combined cycle, regenerative cycle etc…

It is important to highlight that the VFD starter, since it is fully externally cooled, allows have a multiple starts sequence without any problems on winding temperature, while the torque converter could have problems after some attempts; in fact, this equipment, due to its low efficiency (0,6 typically), converts in heat part of the power supplied by the starting motor.

On top of this, the standard starter has obviously some constraints in terms of operating speed since its speed is fixed. This means that it is not easy to adapt the speed as a function of ambient and lube oil temperature and in some extreme conditions start failure sequence may occurs.

Another advantage of the VFD starter system is that, through the Fast cooldown, it allows run the gas turbine at a higher speed during cooldown phase.

The VFD starter will act also as turning device, in this case a DC system, hydraulic type, can be added to have no impacts in case of prolonged loss of electric power.

<u>Helper operating mode</u>

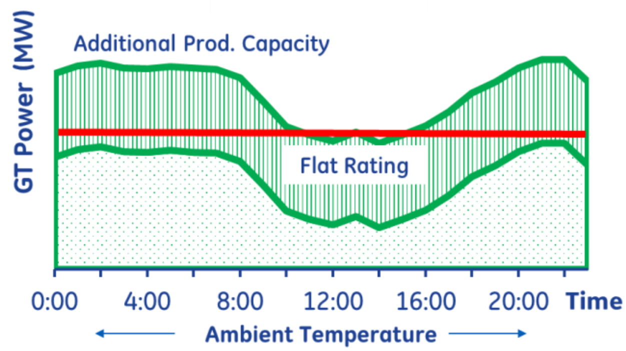

Figure 8 The GT power daily variation

As shown in the picture, during the day the GT power varies as a function of the temperature variation and it can be not sufficient to cover the process demand, in this phase the EM can be used as helper. In fact, by energizing the EM this will start to transfer torque to the HP shaft, this additional torque will lead to a lower torque absorption on the high pressure turbine, so some thermal enthalpy is made available to the lower pressure GT shaft because not necessary anymore to sustain the HP rotor run, consequently the LP shaft power output increases and it is finally transferred to the driven centrifugal compressor. The split of the thermal enthalpy is managed through the variable 2nd Nozzle Guide Vane (NGV), located between the 1st and 2nd turbine wheels and able to split the enthalpy between the HP and LP turbine by the modification of its closure angle.

This means that the power of the electrical machine, by means of the GT thermal cycle, is transferred from the electrical motor to the centrifugal compressor.

This system gives a power gain at GT shaft output that can be controlled to provide more than GT nominal power to the driven centrifugal compressor or at the same nominal power allows the GT run at partial load firing temperature for internal parts life consumption saving.

Here after a simplified formula for the system power gain:

Power gain=(Wt+We*η)/Wtn

Where:

Wt is the thermal power of the GT at the specific ambient conditions

We is the electrical power of the motor

η is the turbine expansion efficiency

Wtn is the nameplate thermal power output of the GT in ISO conditions

In case of a MS5002D GT model the Wtn is 32Mw, so at ISO conditions we have

Power gain=(32MW+5MW*0.9)/32MW=1.14

(HP: Ambient temperature = 15°C, We=5MW, η = 0.9)

Or we may keep the power gain at 1 while reducing the GT firing temperature and give 32MW-5MW*0.9=27.5MW with longer maintenance intervals or, moreover, power gain at 1 at the same firing temperature but at hotter ambient temperatures that, in a standard system, would have not allowed to provide 32MW to the driven machines.

The variation of the power gain is affected mainly by the ambient temperature that drives different behavior on internal thermal flow distributions: higher the ambient temperature higher the benefits and the flexibility for the operator.

Currently, BHGE has developed the 1 MW helper case, while for higher power levels up to 3-5 MW further studies are required.

Generator operating mode

In case of the generator mode, the working concept is the same as per the helper mode but the thermal transfer process will be in the opposite direction with respect the helper mode.

It is important to understand if the generator has to work on prevalent grid only or if it has to run also in island mode (fixed frequency); this difference is important because it has an impact on the electrical machine selection and on the gas turbine operability control system. The generation mode is also very useful where the grid connection for the compressor station is unreliable, or to optimize the opex in case the electricity cost is higher than the fuel cost. In addition, further opex reduction can be obtained when the power generations required by the compressor station is produced by an external generator; this because the generator can be substituted by the hybrid gas turbine and so it can be switched off and left in ready to start condition for emergency purpose only.

Also, emissions and gas turbine efficiency can be improved by this function.

When the process leads to a gas turbine running at partial load condition, this has an effect on the deterioration of the gas turbine efficiency and emissions level because the gas turbine is designed to reach the best performance at full load.

To improve this aspect, by means of the generation mode, it is possible to keep the gas turbine at full power and revert in electricity the surplus of the power that is not absorbed by the compressor.

LP shaft hybrid… Patent pending EP3004601 B1

This configuration is applicable to all GT type (Aero and heavy duty). The EM power range changes basing on the GT model, within two very far limits: 0,5-30 MW

In this configuration the EM is connected directly on the compressor shaft using an high-speed motor and the adoption of a gear box can be avoided.

In case of revamping of the existing unit, the compressor must be modified to implement the mechanical shaft connection with the EM allowing polytropic efficiency increase by adopting latest stage technology. The new configuration will fulfill new plant processes requirements maximizing performances.

By means of the VFD, the EM is able to work at variable speed without any interferences with the operation of the process compressor; this includes the case when the EM is de-energized.

Three modes of operation are possible for the LP shaft configuration:

- Generator
- Helper
- Zero emission running

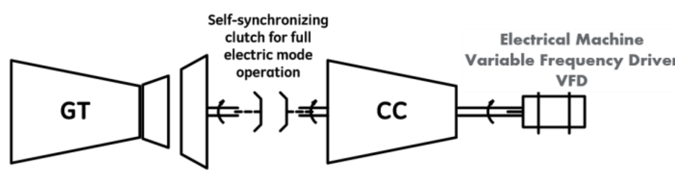

Figure 9 LP shaft hybrid configuration

By definition, an EM machine can act as generator or electric motor and, in this second case, it can work as helper or by running the train by itself (zero emission running).

Here below the three options are described.

Generator operating mode

The EM is installed on the same shaft of the train and absorbs power from the GT, whenever the GT delivered power is greater than the power required by the compressor this is converted into electrical power. Since the machine has the possibility to modulate the generator resistant torque in a wide speed range, the power produced by the generator can be modulated without any interference with the process.

Using the EM as generator keeps the power output of the gas turbine constantly high, notwithstanding the actual power request from the compressor(s); this allows maximize the efficiency of the gas turbine even if it causes the fuel consumption and the emissions increase.

Helper operating mode

In case of GT lack of power, the EM can be energized converting electricity into power available for the

compressor.
The helper can:
- Increase the power availability to the compressor(s)
- Share the power demand from the compressor(s) between GT and EM

The first option increases the production, while the benefits of the second one are:
• reduction of the operation cost (life extension, selection of primary energy source)
• reduction of emissions

Economics can play a role in showing how optimally it is possible to shift towards a low carbon and resource efficient economy.

In a case study developed for a BHGE operator, a mechanical drive configuration with a PGT25 GT model (23.3 MW at ISO conditions) fueled with natural gas coupled with a 10 MW electric motor and operated in hybrid mode for 3800 hours/year we are able to save 9% of cost of primary energy source (fuel) and 26% of carbon taxes. In addition maintenance intervals extension should be considered.

The behavior of the fuel consumption, thermal efficiency (1/heat rate) as well as the emissions vs the GT power output is shown in Figure 10 and Figure 11.

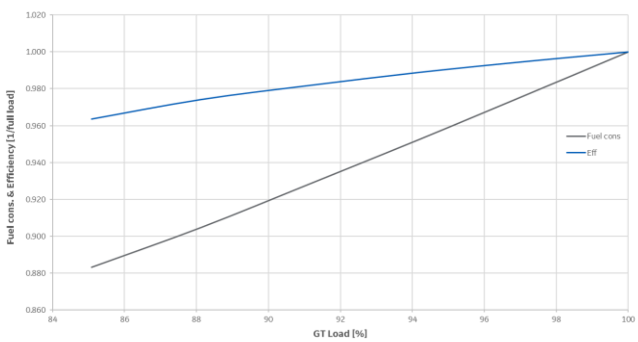

Figure 10 GT fuel consumption and efficiency vs power output

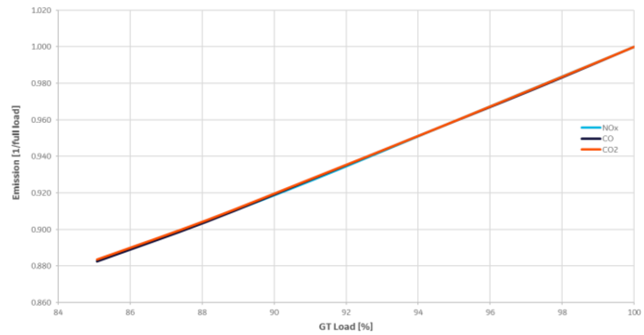

Figure 11 GT emissions vs power output

<u>Electric motor in "Zero emissions" configuration</u>

As extreme application of the helper operating mode, the EM can be dimensioned to deliver the total or partial amount of power required by the compressor(s) allowing to produce without emissions. Thanks to the adoption of a self-synchronizing clutch, located between the compressor and the GT, it will be possible to drive the centrifugal compressor only with the EM and so to keep the GT stopped; this will avoid loss of production in case an emergency shut-down occurs or some maintenance activities (i.e. air filters, emergency/safety loop checks) are required.

INTEGRATION WITH RENEWABLE ENERGY

The combination between the electrical machine and the gas turbine allows also integrate the turbo-compressor train with the green electricity produced, for example, by the renewable energy sources.

In fact, in case of the availability of the green electricity, it is possible to energize the electrical machine that generates power. In order to keep the process compressor at the speed set point, the fuel regulator decreases the fuel flow to compensate the additional power fed by the electric motor. The abatement of the fuel leads to a CO_2 footprint reduction showing huge environmental and economic benefits.

Starting from one of the developed case studies, as for a mechanical drive configuration with a LT16 GT model (16.8 MW at ISO conditions) fueled with natural gas coupled with a 16 MW electric motor and operated in "zero emission running" mode for 2400 hours/year we are able to save 18% of cost of primary energy source (fuel) and 29% of carbon taxes.

ENERGY STORAGE

Another advantage of the hybrid configuration is that, in case of pipeline application, it allows energy storage operation mode by the pressure accumulation.

In fact, during the “zero emission” running mode, the compressor driven by the electric motor will deliver flow and pressure to the pipeline that acts as energy tank storage, this in case that the network consumption is lower than the compressor flow. This difference between consumption and compression leads to a pressure increase and such energy, produced in the “zero emission” running mode, can be used to delay the gas turbine start up and consequently to reduce the service factor of the GT (number of required yearly running hours with respect the full year calendar hours).

POWER MANAGEMENT & CONTROL
Since in a plant there are many variables strictly connected each other, for an operator is quite impossible to evaluate how to proper balance the GT fuel and Power controllers so BHGE is going to develop a specific software (Smart Energy Balance) that manages this trade off optimization.

CONCLUSION

In this paper, all the benefits and possible configurations related to a smart synergy between gas turbine and electrical machine have been described, and four main aspects have been highlighted:

- Power production increase
- Maintenance life extension
- Opex reduction
- Integration with renewable

The hybrid configuration offers a wide range of application to optimize power and the maintenance parts life.

This kind of solution allows have a flexible system which is adapting to the operator needs with a dynamic control strategy.

The importance of this synergy is the new vision on how the gas turbine can intercept the new market trend of renewable integration in the existing industrial plants, matching the process needs with opex and emissions optimization.

ACKNOWLEDGMENTS

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Giampaolo Gabbi for the cycle deck models utilized to quantify the effects of the EM on the GT thermodynamic cycle.

Sarti Giovanni as system engineer that executed with depth knowledge the coordination among all the involved technical disciplines.

NOMENCLATURE

CC=Centrifugal compressor
DC=Direct Current
EM=Electrical machine
GT=Gas Turbine
GB=Gear box
HP=Gas turbine high pressure shaft
HP comp=High Pressure compressor
LP=Gas turbine low pressure shaft
LP comp=Low Pressure compressor
LNG=Liquified natural gas
MTTR=Mean time to repair
NGV=nozzle guide vane
OPEX=Operating expenditure
VFD= Variable Frequency Drive

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