USE OF 690 V FOR LV INDUSTRIAL DISTRIBUTION NETWORK TO SAVE CAPITAL COST AND IMPROVE NETWORK EFFICIENCY

P.F.Lionetto, R.Brambilla — FWI-Foster Wheeler Italiana, Milan - Italy

P.Vezzani — Tecnimont, Milan - Italy

E.Picatoste — Iberdrola, Madrid - Spain

SUMMARY

The most common voltage used in European industrial plants to supply the LV electrical distribution system is 400 V. This level is largely used because is the same voltage level used for the public electrical distribution network, so that equipment, apparatus and components are easily available on the market.
However, the adoption of a higher voltage level presents some advantages, mainly in term of capital cost saving and network efficiency improvement; this might make this choice quite interesting and convenient.
To verify the above statement, a detailed analysis has been performed during the basic design of the electrical system of a new industrial installation, characterised by a total consumption of about 180 MW, 40% of which fed at LV level.
The target of the analysis was to demonstrate the convenience of the 690 V for the LV distribution/utilisation system, respect to the 400 V.
Starting from the knowledge of the user loads, a detailed comparison between the two alternative solutions has been performed, focusing in particular the following main points:

- size and cost of induction motors;
- max. load current and fault duty of the switching apparatus available on the market;
- cable voltage drop and cable cross section;
- sizing and number of feeding transformers;
- power losses.

The paper gives a general view of the approach used in the study and presents several examples related to the analysed plant.
Many tables make easy, for each one of the analysed factors, the comparison between the two solutions and facilitate the analysis of the results.
The study identified size and motors number as the key factors that may lead to replace 400V with 690 V and so allowed to define general criteria that may be used for any specific installation.

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INTRODUCTION

The most common voltage used in European industrial installations to feed LV electrical distribution network is 400 V. This voltage level is largely applied since it is the same voltage used for public distribution network, so that equipment, apparatus and components are easily available on the market.
The 400 V voltage level is usually associated in industrial plant to 6000 V to feed MV users, typically motors. The use of these two voltage levels allows to install well tested equipment and machinery of standardised characteristics, that may be provided by a large number of manufacturers.
However the adoption of a higher "low voltage" level (i.e. 690 V) offers some advantages that might make this choice quite interesting and convenient; the main advantages relate to capital cost saving and improvement of global network efficiency .

Several key-factors must be taken into account to compare the two alternatives (i.e. 690 and 400 V), i.e.:

- Size and cost of induction motors;
- Max. load current and fault duty of the switching apparatus available on the market;
- Cable voltage drop during normal operating condition and at motor start-up;
- Cable cross section;
- Sizing and number of feeding transformers;
- Total power losses.

All the above items have been deeply analysed during the basic design of the distribution system of a new Integrated Gasification Combined Cycle Plant (IGCC), characterized by a load consumption of about 180 MW, 40% of which are motors fed at LV level.
The aim of the study was to verify the real convenience to make use of 690 V rather than 400 V, taking into account the impact on the market; the results allowed to state some general rules that can be used for any specific installations.

IGCC PLANT DESCRIPTION

The plant is a future IGCC, characterized by a generation of 980 MW of electrical energy, by burning the syngas, obtained by the gasification of residue oil in refinery, in two gas turbines, assembled to form a Combined Cycle. The chemical process is based on a partial oxidation of the feedstock carbon content, with pure oxygen and HP steam (as feedstock atomiser and reaction moderator), producing a syngas rich in CO and H2. Oxygen is obtained by air distillation from a cryogenic plant installed inside the complex.
The syngas emerging from the gasifiers is treated and cleaned to be conducted to the gas turbines in the Combined Cycle.
The complex requires a load demand of about 180 MW, including the auxiliary service of the combined cycle. The majority of the load (about 130 MW) is related to Air distillation plant, to obtain the oxygen, characterised by two trains each one including three very large motors (air-compressor – 30 MW; nitrogen compressor-25 MW; oxygen compressor - 10 MW).
The remaining loads are related to three main Process Units, i.e. Gasification Unit, Utilities Unit common to all the plant, and Combined Cycle Unit. They are characterized by different size of induction motors as pointed out in table N. 1.

Motor size [kW]	5.5	11	30	45	90	160	200	250
Motor number	63	38	30	16	24	10	2	8
Motor size [kW]	350	500	630	800	1200	1400	1800	2200
Motor number	9	13	2	4	2	3	2	4

Table N° 1 – Motor size and motor number installed in the three main Process Units.

KEY POINTS ANALYSIS

Induction motors

One of the key points in the comparison between 400V and 690 V is the capital cost of the induction motors .
On European market, 690 V motors are available in the range 0.18 - 1000 kW with totally enclosed fan cooled construction and up 630 kW with EEx-d, EEx-e, Ex-n protection type for hazardous area (EEx-p for larger motor size).
It is common practice in industry to use 400 V motors up to 160-200 kW to keep voltage drop during normal and start-up condition within acceptable limits up to the distance of about 200 m; higher size motors are fed at 6000 V.
In general the capital cost of 690 V motors is the same of 400 V motors; on the contrary, the capital cost of

6kV motor is about two-to-three time higher than the corresponding size of LV motor.
From this, the more is the number of motors that can be fed at 690 V instead of 6000V, the more is the capital cost saving.
To evaluate the capital cost saving it is mandatory to establish the upper motor size that can be fed at 690 V.

Switchboards and Switching Equipment

LV switchboard are generally designed, with regard to dielectric withstand, for voltage up to 690V. Therefore the LV switchboards of standard manufacturing can be used either at 400 V or at 690 V.
On the other hand, short circuit breaking and making capacity of circuit breakers, motor starter and any switching devices are strongly de-rated when the operating voltage increases.

In general when used at 690 V, the fault duty capacity is reduced, compared to the corresponding 400 V ratings, in the range of 65-75%, for moulded-case circuit breakers, and 15-25%, for open-air circuit breakers.
Moreover, for 690V level, the manufacturers certify motor protection co-ordination (i.e. fuses and contactors, moulded-case circuit breaker and contactors, limitors and contactors) only up to 50 kA and for motor size up to 350 kW. Open-air circuit breakers with higher breaking capacity could be used, but they are available only for motor starter above 300 kW.
Consequently by using 690 V the fault level of 50 kA shall not be exceeded; that limitation does not exist for 400 V voltage level, although a fault duty above 50 kA is usually not recommended for a good engineering practice.

With regard to motor starters, different solutions are possible. Co-ordinated moulded-case circuit breaker and contactor combination is available up to 315 kW and 335 kW respectively for 400V and 690 V rated voltage. In the latter case the moulded case circuit breaker shall be current-limiting type, with a capital cost increase of about 20%.
Fuse-contactor combination represents a cheaper solution than the moulded-case circuit breaker and contactor combination (less capital cost of about 40% to 20% from low to high ratings) and offers a most reliable short circuit protection level also at the highest fault duties. Again, the co-ordination is ensured up to the same limits of moulded-case circuit breakers.
For motor sized above 355 kW, motorised open-air circuit breakers shall be used for 690 V voltage.

Cables

LV cables, rated 0.6/1 kV, can be used either for 400 V or 690 V without affecting insulation withstand.
With respect to cable “ampacity”, the use of 690 V motors, involving a lower load currents than 400 V, makes possible to reduce both cable conductor cross section (keeping the same voltage drop in both cases) and cable power losses. In alternative, the same cross section can be used to feed, with the same voltage drop, motors located at longer distance or larger in size.
The reduction of cross section is true for motor rating above 5.5 kW, since for smaller motor sizing cable cross section is determined, both for 400 and 690 V, by the maximum let-through-energy.
For motors above 200 kW, the use of 690 V requires cables with a cross section larger than in case of motors of the same size fed at 6000 V. Capital and operating costs are therefore greater, as the cost of conductor material is prevalent in cable cost.

LV Transformers

The use of 690 V instead of 400 V implies the possibility to increase transformer rated power. Its maximum value is, however, limited by fault current duty on LV switchboards and their switching devices and motor starters. Since the figure of 50 kA shall not be exceeded, motor contribution included, the ratings of LV transformers shall not exceed 3.15 MVA, with a short circuit impedance not below 6-7%.
Consequently, as a lot of motors, usually fed at 6000V, shall be fed at 690V, the number of LV transformers shall increase with respect to the ones necessary with 400V. Further, if the electrical scheme is arranged so that the LV network is drawn in cascade from 6000V, no reduction in MV transformer size is achievable. Therefore, the increase of 690 V transformer number involves a rise both in capital cost and in transformers power losses.
It becomes more convenient, where possible, to draw the 690 V distribution system directly from primary MV distribution network (i.e.15 kV or 33 kV).

Upper size of 690V motors

The upper motor size to be fed at 690 V can be individuated by fixing, at motor starting condition, the same maximum voltage drop accepted for the 400V motors (max 200 kW), taking into account also the equivalent impedance of supply transformers.
Calculations (Tab.2) have been carried out assuming a cable length of 200 m and a motor starting current 6.5 times the respective rated current.
The assumed maximum allowable bus voltage drop during motor starting is 10%, with the voltage at motor terminals not below 80% of rated voltage.
From the table the upper limit of 690V motor size is about 630 – 800 kW. Motors above these sizes shall be fed at 6000 V.

	Voltage			
	400V	**690V**		
kW	200	200	630	800
cable	2(3x185)	3x240	3(3x240)	4(3x240)
ΔV mot [%]	13.9	10.4	14.5	18.2
ΔV bus [%]	5.3	3.7	8.56	10

Table N° 2 – Voltage drop during motor starting

KEY POINTS CRITERIA APPLIED TO THE IGCC PLANT

As a general rule to compare the two alternatives (i.e. 400 V and 690 V), all the above considerations shall be taken into account and quantified from economical point of view. Motors, motor starters and network components capital costs shall be evaluated along with cables and transformers capitalised power losses.
For the specific IGCC plant the application of the above criteria is below illustrated.
Capital cost evaluation shall include:

- motor feeders, complete of motor, cable, motor starter and switching protective device;
- LV transformers and transformer feeders;
- LV switchboards, composed of two incomers and one tie-breaker (secondary selective scheme).

Motor feeder capital cost

The cost of 400 V, 690 V and 6000 V motor feeders are shown in Table N° 3, referring to each motor size. The combination of fuse and contactor has been considered for 400 V and 6000 V motors up to 1200 kW. The same arrangement has been taken into account for 690 V for motor ratings up to 250 kW; open-air circuit breaker for higher size.

Motor size [kW]	400 V		6000 V		690 V	
	Cable type	Capital cost [M€]	Cable type	Capital cost [M€]	Cable type	Capital cost [M€]
5.5	3x4	0.0016	-	-	3x4	0.0016
11	3x6	0.0023	-	-	3x4	0.0022
30	3x25	0.0043	-	-	3x10	0.0037
45	3x35	0.0059	-	-	3x16	0.0052
90	3x120	0.102	-	-	3x70	0.0092
160	2(3x120)	0.0195	-	-	3x150	0.0171
200	2(3x185)	0.0231	-	-	3x240	0.0200
250	-	-	3x25	0.0509	2(3x120)	0.0230
350 (*)	-	-	3x25	0.0569	2(3x150)	0.0333
500 (*)	-	-	3x25	0.0591	2(3x240)	0.0390
630 (*)	-	-	3x35	0.0657	3(3x240)	0.0453
800 (*)	-	-	3x70	0.079	4(3x240)	0.0619

Table N° 3 – Capital cost of each motor feeder (fuse & contactor combination. (*) Open-air c. breaker - 690V.

Motor size [kW]	Total motors	400 V capital cost [M€]	6000 V capital cost [M€]	690 V capital cost [M€]
5.5	63	0.100	-	0.100
11	38	0.0864	-	0.0836
30	30	0.1291	-	0.1127
45	16	0.0947	-	0.0831
90	24	0.2452	-	0.219
160	10	0.1949	-	0.1712
200	2	0.0461	-	0.040
250	8	-	0.4076	0.1840
350	9	-	0.512	0.300
500	13	-	0.768	0.510
630	2	-	0.132	0.091
800	4	-	0.316	0.2479

Table N° 4 – Total capital cost of motor feeders up to 800 kW of the entire plant

From the table, the 690 V motor feeder capital cost is from 20 to 60% less than the corresponding 6000 V one.

Considering at the first stage only the motors sized up to 800 kW (i.e. the upper motor that can be fed at 690V), the total motor feeders capital costs of the plant are listed in table N° 4.

Transformer and switchboard capital cost

A primary distribution system, operating at 33 kV, is used to feed the three Process Units of the plant.
In case of 400 V it is necessary to provide a secondary MV distribution system (6000V) to feed motor sized above 200 kW. With 690 V choice, provided that only motors up to 800 kW are present, the 6000 V level is not necessary.

To compare the two choices (i.e. 400 V and 690 V) it is necessary to determine the number of LV and MV transformers, required to feed the total load, . Referring to the specific case under examination, each Process Unit is fed by a proper Load Centre, whose electrical system is arranged, for reliability reasons, according to the secondary selective scheme.

Again, considering only the motors sized up to 800 kW, the solution 400–6000 V requires two LV (2 MVA) and two MV (4.5 MVA) transformers for each Process Unit, provided a contemporary and an utilisation factor of 0.6 and 0.9 respectively (Fig.1).
To minimise transformer losses, the 400 V system is directly fed from primary distribution system at 33 kV and not in cascade from 6 kV system.

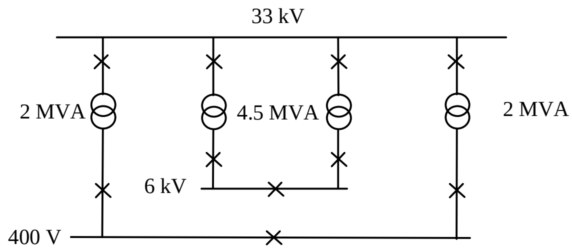

Fig.1 Simplified single line diagram of each process unit based on 6kV and 400V distribution voltages.

On the other hand, for the 690 V solution, twelve LV transformers (four for each Process Unit) are necessary, each sized 3.15 MVA (Fig.2).

The costs of the distribution network, i.e. transformer feeders and switchboards, for the two choices are shown in table N° 5.

The transformer capital cost includes:

- LV (MV) transformer;
- LV (MV) secondary outgoing feeder, bus (cable) type, 30 m length.

33 kV incoming transformer feeder includes a cable of 300 m length and a 33 kV switching device in cubicle.

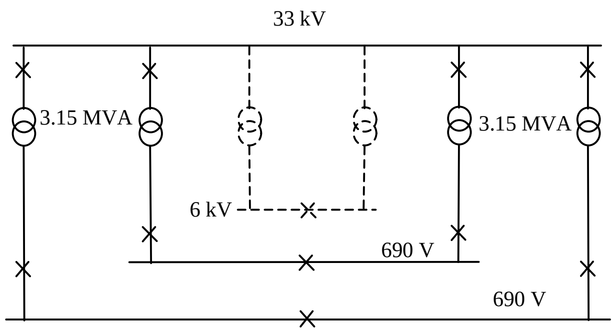

Fig.2 Simplified single line diagram of each process unit with 690 V (and 6kV) distribution voltages.

The LV & MV switchboards cost refers to two incoming circuit breakers and one tie breaker.

ITEM	Each [M €]	400 V		6000 V		690 V	
		N°	Total [M €]	N°	Total [M €]	N°	Total [M €]
33 kV transf. feeder	0.026	6	0.156	6	0.156	12	0.313
6 kV transformer	0.046	-	-	6	0.276	-	-
6 kV switchboard	0.055	-	-	3	0.165	-	-
400 V transformer	0.019	6	0.114	-	-	-	-
400 V switchboard	0.054	3	0.162	-	-	-	-
690 V transformer	0.032	-	-	-	-	12	0.384
690 V switchboard	0.054	-		-		6	0.324
Total cost of 400 V & 6 kV. network [M €]							**1.029**
Total cost 690 V network [M €]							**1.021**

Table N° 5 – Capital cost of distribution network (up to 800 kW motors only)

Capitalised Cost of Distribution Network Losses

Cable feeder and transformer power losses, evaluated for both the solutions, are capitalised on the basis of five year pay-back period, 7000 hours per year of operation, interest rate of 7% and 0.0363 Euro per kWh cost. In this way the costs of power losses can be added to the capital cost of network and motor feeders.

The results for capitalised cable feeder and transformer losses are indicated in the tables N° 6 and 7.
The capitalised network losses of 690V system are in this case slightly higher than those of 400V-6000V system due to the higher losses of 690V cables respect to those at 6000V.

Motor size [kW]	Total motors	Cable losses capitalised cost [M€]		
		400 V	6000 V	690 V
5.5	63	0.016	-	0.0054
11	38	0.0255	-	0.0128
30	30	0.0353	-	0.0291
45	16	0.0299	-	0.0221
90	24	0.0513	-	0.0293
160	10	0.0338	-	0.0181
200	2	0.0068	-	0.0037
250	8	-	0.0027	0.0222
350	9	-	0.0061	0.0317
500	13	-	0.0178	0.0605
600	2	-	0.00314	0.0123
800	4	-	0.0052	0.0245

Table N°6 - Capitalised cable losses

Total losses [M€]	400 V	6000 V	690 V
cable	0.1986	0.0349	0.272
transformer	0.044	0.094	0.130
Distribution network (400 & 6000 V) [M€]			0.371
Distribution network (690 V) [M€]			0.402

Table N° 7 – Capitalised network total losses

OVERALL PLANT CAPITAL COST

The overall capital cost for the two solutions are compared in the following table N° 8:

items	400 V & 6000 V		690 V		Cost saving
	[M€]	[%]	[M€]	[%]	[M€]
Motor feeder total cost	3.032	68.5	2.143	60.1	-0.889
Distribution Network total cost	1.029	23	1.021	28.6	-0.008
Network losses total cost	0.371	8.5	0.402	11.3	+0.031
Total cost	4.432	100	3.566	100	-0.866

Table N° 8 – total Cost comparison between the two solutions 400V&6000V and 690 V (motors up to 800 kW only)

From the table, a total capital cost saving of about 20% may be achieved when using 690 V instead of 400 V.
The factor which plays the most important role in cost saving is the motor cost. On the contrary, distribution network and power losses costs have scarce weight.
Therefore, the more is the number of motors with size in the range 250 – 800 kW the more is the saving.
Anyway, this result shall be carefully considered: in fact it shall be remarked that, if the plant includes also motors above 800kW (see table N°1), the 690V choice requires a further 6000 V system (see fig.2).
The new calculation, performed taking into account the true condition, reduces the capital cost saving at about 8%, with the different weights as per table N°9.

items	400 V - 6000 V		690 V –6000V		Cost saving
	[M€]	[%]	[M€]	[%]	[M€]
Motor feeder total cost	4.3952	71.5	3.5062	62.5	-0.889
Distribution Network total cost	1.24	20	1.621	28.5	+0.381
Network losses total cost	0.4865	8.5	0.5205	9	+0.034
Total cost	6.1217	100	5.6477	100	-0.474

Table N°9 – weight of different items on total capital cost

From what above the cost of motor feeder still results the main factor on cost saving; the increase on distribution network caused by the need of a new MV system is not sufficient to affect the advantage in motor cost saving.

Finally, in case of LV distribution system drawn in cascade from 6 kV system, the same calculations, reported in the Table N° 10, show the reduction of total capital cost saving to 5%.

items	400 V - 6000 V		690 V		Cost saving
	[M€]	[%]	[M€]	[%]	[M€]
Motor feeder total cost	4.3952	70	3.5057	59	-0.889
Distribution Network total cost	1.316	21	1.858	31	+0.542
Network losses total cost	0.546	9	0.582	10.	+0.036
Total cost	6.257	100	5.946	100	-0.311

Table N°10 – Total capital cost in case of LV system in cascade from 6000 V network.

Anyway this arrangement shall not be recommended by a good engineering practice, because of higher network capital cost and transformer losses.

CONCLUSION

The paper has illustrated the economical benefits that can be achieved, in industrial installation, by replacing the most common 400 V system with 690 V.
The k-point in capital cost saving is the lower cost of 690 V motor (from 20 to 60% less) compared to the corresponding 6000 V motor.

Anyway, other factors reduce the above advantage.
First of all, the need to install more 690 V transformers due to the derating of switching devices fault duty when operating at 690 V.
Secondly, it is necessary to make use of a 400/230 V system to feed small motors (below 0.18 kW) and particular users (i.e. lighting, heaters, etc.).
Moreover, the limited number of manufacturers capable to provide 690 V motors and to certificate motor protection co-ordination, may adversely affect the choice of 690 V.

However, as a general rule, when an industrial plant is characterized by a large number of motors sized in the range 200 – 630 kW, the 690 V solution should be recommended. In the next future with the increase of EU market, a wider use of 690 V in industrial application should be expected.

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