Designing Power Supply Along a 1500km Pipeline: Challenges & Solutions

Paper No. PCIC25_20

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Abstract - Designing electrical systems for highly atypical networks supplying pumping, long line heat tracing and pressure reduction substations along a 1500km pipeline poses unique challenges. This is the case of the project called EACOP for Eastern African Crude Oil Pipeline. This article explores the implications of such networks on equipment selection, neutral grounding system implementation, transformer and motor energization, voltage plan, voltage management, and protection systems. Many studies have been carried out to understand the constraints imposed on these atypical networks and will be presented as well as the solutions provided to reduce the risks. Additionally, the paper will incorporate insights from the end user, who will contribute best practices based on prior experiences.

Index Terms — pipeline, heat tracing, extended cable network, power system studies, capacitive currents, neutral earthing system, protection system, voltage control.

I. INTRODUCTION

For large and extended electrical MV networks such as a 1500km pipeline that is required to supply MV pumps, heat tracing systems and some auxiliary loads, the general rules, state of the arts & methodology cannot be applied directly. Indeed, the very long cable length, low short circuit power mainly will result in many challenges to be solved.

This article will focus on some of the challenges and the solutions used in the project to overtake them. The items are MV equipment selection, neutral grounding systems design, transformer energization, protection systems and voltage / reactive power controls. The main objectives are to keep standard market equipment, easy to operate and maintain.

The first part will describe the application of the pipeline, the main electrical architecture, main MV equipment loads and power generation, and the required controls. Then, each challenge will be deeply investigated, its solution as well. Finally, we will finish by a conclusion.

II. SYSTEM DESCRIPTION

A. Application

The project consists of a 1500km pipeline connecting two central processing facilities (CPFs) in Uganda where oil is extracted to Tanzania where tankers will collect the oil. For transmitting the oil in a so long distance, some subsystems are required such as regular long line heat tracing systems (LLHT) to heat the pipeline to avoid any mud. The LLHT is activated depending on the oil flow rate in the pipe. LLHT substations are installed every 60km around. Also, pumping stations (PS) are also necessary to push the oil in the pipe as well as pressure reduction station (PRS) mainly due to relief of the area. Finally, generation system (Crude Oil generators, PV plants, Grid connections) is in place to supply all those subsystems and utilities.

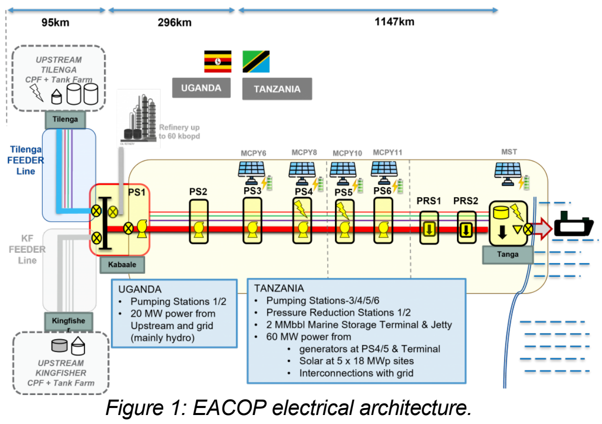

Figure 1: EACOP electrical architecture.

B. Electrical network topology

From electrical prospectives, the pipeline is split in four different and independent sections called section 1, 2, 3 and 4, of roughly 400km each.

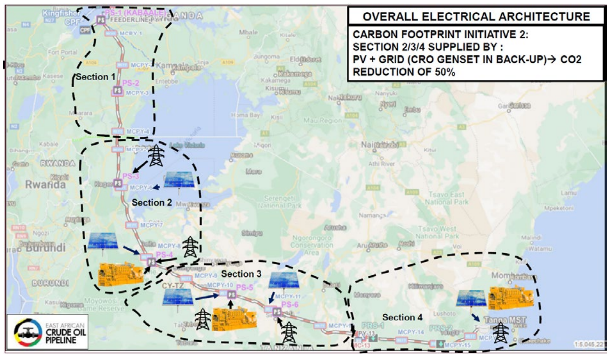

Figure 2: Overall electrical architecture of the 4 sections.

Section 1 is in Uganda, where crude oil is extracted from two CPFs: Tilenga CPF and KingFisher CPF. From an electrical standpoint, a 66 kV hub has been established to connect Tilenga CPF, which is 100 km from the substation to KingFisher CPF, located 50 km from the substation. The 66 kV substation is linked to the 132 kV grid. A 66 kV feeder from the substation supplies the pipeline and its utilities for Section 1.

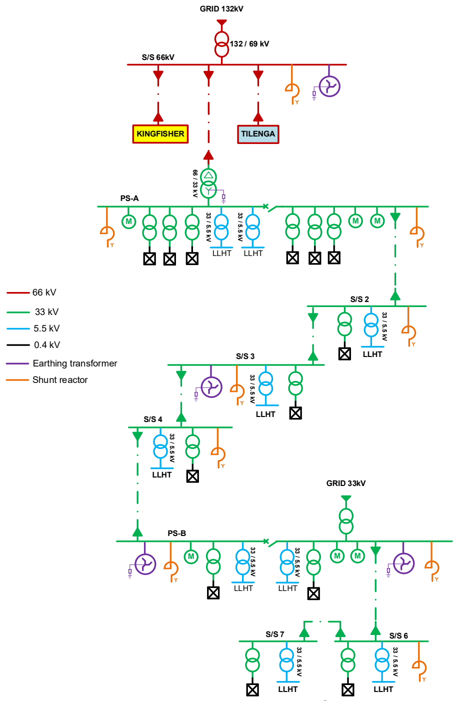

Figure 3: single line diagram – Section 1.

Sections 2, 3 & 4 are in Tanzania. Sections 2 & 3 are similar where a power station of 6 crude oil generators (5.2MVA each) supplies the electrical system. In the power station, there are also all auxiliary's system and pumping motors. Then, a 33kV backbone cable supplies the other substation: pumping station, LLHT substations and other auxiliary systems. The total cable length is around 400km.

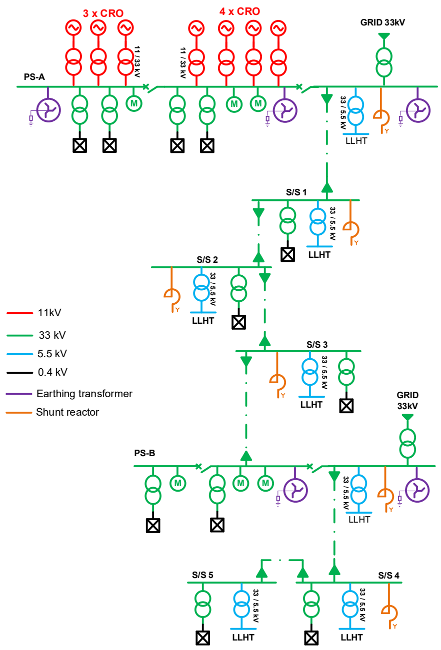

Figure 4: single line diagram – Section 2

Section 4 is the final section of the pipeline. It is slightly different of the others. Indeed, the power generation in 11kV with 7 crude oil generators (5.2MVA) which supplies the internal terminal system including the jetty in 11kV, and in 33kV, the pipeline with the LLHT substations and pressure reduction stations.

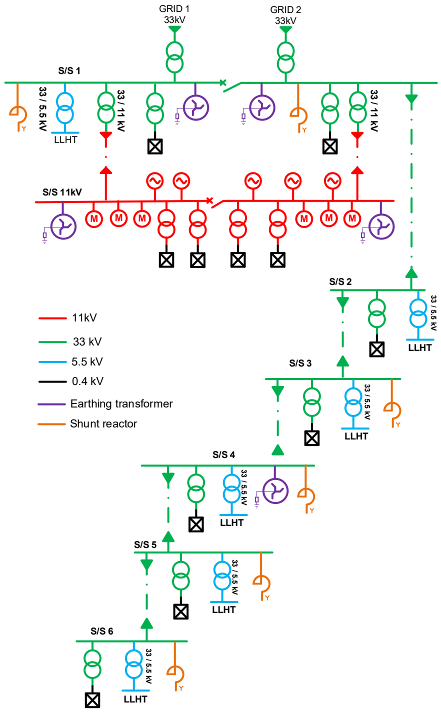

Figure 5: single line diagram – Section 4.

II. CHALLENGES & SOLUTIONS

The main specificity of those different electrical networks is the unusual HV cable length, roughly 400km per section by underground cables. Those cables generate a high level of capacitive current (power) of about several hundred of Amps. Combined with low & variable short circuit powers, large variation loads and use, when possible, of standard & conventional products, it brings many challenges to have an efficient & reliable power system.

- MV switchboard selection
- Neutral earthing system design,
- Electrical Protection system,
- Voltage & reactive power controls,
- Transformer energization,
- 33kV cable energization,
- Harmonic constraints.

The below chapters describe all above challenges with the solution adopted in the project.

A. *MV switchboard selection*

One of the main & key equipment in the 33kV backbone system is the MV switchboard. The criteria to select a MV switchboard is in general very simple. Indeed, the main characteristics depends on short circuit current values, load current, system voltages, technology - GIS / Air… -, footprint... In this particular electrical network, the short circuit current value is quite low (less than 12.5 kA) and the load current is within the standard. The system voltage is also not restrictive as it is 33kV+/- 10%. But, as opposite to conventional project (refinery for instance), there is one fundamental parameter to be compliant with, it regards the cable charging current that the circuit breakers must break.

Indeed, the extensive cable length generates a high level of capacitive current, around 400 A per phase during no-load operation, at its rated voltage. This capacitive current is called cable charging current.

This will induce two main issues, one regarding the reactive power generated by the cables absorbed by the crude oil generators. It could be an issue if the reactive power is in too many quantities for the crude oil generators and could lead to instability issues in the electrical network.

Second issue is related to the switching off the breaker with high level of cable current also called cable charging current. The IEC 62271-100 standard gives tests to be done to certify the compliance of the MV switchboards for different parameters. Two tests are presented, one for capacitive current switching and the other for line/cable charging current.

	Line	Cable	Single capacitor bank	Back-to-back capacitor bank		
Rated voltage U_r kV, r.m.s.	Rated line-charging breaking current I_l A, r.m.s.	Rated cable-charging breaking current I_c A, r.m.s.	Rated single capacitor bank breaking current I_{sb} A, r.m.s.	Rated back-to-back capacitor bank breaking current I_{bb} A, r.m.s.	Rated back-to-back capacitor bank inrush making current I_{bi} kA, peak	Frequency of the inrush current f_{bi} Hz
3,6	10	10	400	400	20	4 250
4,76	10	10	400	400	20	4 250
7,2	10	10	400	400	20	4 250
8,25	10	10	400	400	20	4 250
12	10	25	400	400	20	4 250
15	10	25	400	400	20	4 250
17,5	10	31,5	400	400	20	4 250
24	10	31,5	400	400	20	4 250
25,8	10	31,5	400	400	20	4 250
36	10	50	400	400	20	4 250
38	10	50	400	400	20	4 250
48,3	10	80	400	400	20	4 250
52	10	80	400	400	20	4 250

Figure 6: Cable charging current – test table – IEC 62271-100.

For EACOP project, the selected MV switchboards at the offer stage did not comply with the system cable charging current value. In other words, it means that the MV circuit breaker was not able to break and could be damaged. Therefore, it was necessary to find a new MV switchboard and CB range compliant. Main impacts of this change project wise was its cost and the layout, which leads to a much bigger ehouse.

B. *33kV neutral earthing system design*

In general, the design of the MV neutral earthing system of an electrical network is quite simple. Indeed, the choice depends on different criteria such as current level limitations, protection system, system availability, cost…

For a plant electrical network, the choice in MV is often resistance grounded as it is simple to be installed, and easy to detect an earth fault, and sufficiently low to prevent any big damages to the rotating machines if any. For such network, the sizing of the resistance / impedance is depending on the capacitive current of the system, and the state of the art is to size it to get a limiting current greater than twice the capacitive current.

However, for an extended electrical network such as EACOP, following this relationship is not enough and will/could lead to some overvoltage issue and fault detection.

The IEC 60071-2 gives a graph with the X0/X1 factor and its overvoltage factor. X0 is the zero-sequence reactance of the system and X1 is the positive phase sequence system.

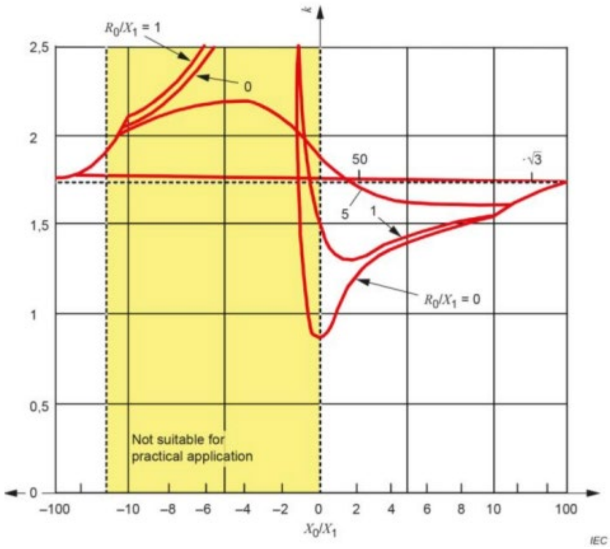

Figure 7: Graph X0/X1 versus overvoltage factor – IEC 60071-2.

In other words, it means overvoltage can be significant and destructive for the equipment in case of earth fault, if the ratio X0/X1 is negative. A parametric analysis has been performed to evaluate the X0/X1 ratio depending on cable length for different neutral earthing systems. It shows that the split between negative and positive values occurs at between 130km to 160km. It means that after 150km of cable length, the risk to get a destructive overvoltage is high. It is therefore necessary to install and connect at least two to three neutral earthing system equipment to always get a positive X0/X1 whatever the cable length and the fault location. The earthing equipment are connected to different substations (distant of around 100 km).

The sizing will be performed according to IEEE C62.92.1-1 recommendations when possible.

Ratios of symmetrical component parameters			Percentage fault current	Per unit transient LG voltage
X0/X1	R0/X1	R0/X0		
0-10	/	>2	<25	<2.5

Figure 8: Extract from IEEE C62.92.1-1.

While X0/X1 factor is important and IEEE standard gives recommendations for sizing, one other key parameter is the detection of the earth fault by the protection system when an earth fault occurs in the electrical network. The earth fault detection is based on overcurrent directional protections (ANSI 67N). Hence, the design of the neutral earthing equipment's shall allow the protection discrimination at upstream or downstream side of the protection function. In other words, to have a significant angle difference (minimum 70°) between an upstream fault and a downstream fault viewed by the protection relay. The below tables show an example of results for the X0/X1 and angle difference after designing the neutral earthing equipment and locate them at substations:

Supply by PS1-Tilenga / Supply by PS2	PS1	B07	B10	B15	PS2	B20	B22
	6,01	4,59	1,67	3,26	3,48	5,94	6,22
	3,08	3,47	1,54	3,17	3,45	5,93	6,21
	3,28	6,20	1,42	3,11	3,44	5,93	6,21
	2,37	2,53	1,14	5,77	4,54	6,54	6,71
	2,37	2,56	1,20	2,88	4,32	6,46	6,65
	2,40	2,51	**0,96**	1,29	**0,83**	off	off
	2,41	2,52	**0,97**	1,31	**0,86**	2,38	off
	2,41	2,53	**0,97**	1,32	**0,87**	2,40	2,85

Figure 9: Example of X0/X1 factor for a section.

Fault location	SWG	From	To	3I0 (A)	Angle (U0/I0)
PS1	B10	B10	B15	61	52
B07	B10	B10	B15	84	52
B10	B10	B10	B15	130	52
B15	B10	B10	B15	362,00	-118,50
PS2	B10	B10	B15	211,00	-118,50
B20	B10	B10	B15	123,00	-118,50
B22	B10	B10	B15	103,00	-118,50

Fault location	SWG	From	To	3I0 (A)	Angle (U0/I0)
PS1	B15	B15	B10	86	-120,44
B07	B15	B15	B10	119	-120,44
B10	B15	B15	B10	184	-120,44

Figure 10: Example of phase angle seen by protection relay for different earth fault locations.

In the above tables, the two criteria are fulfilled, hence, the overvoltage will be limited and not be destructive for the equipment's, and the earth fault detection will be possible; the earth fault will be cleared in a selective manner.

In terms of design, the neutral earthing equipment is a combination of reactance (for getting a positive X0/X1) and resistance (to get a phase angle different between an upstream and a downstream fault. Here is an example of characteristics:

Equipments	Reactance value: X0-TR (ohm)	Resistance value: Rn (ohm)	Current flowing the zero-sequence generator (kA): 3*I0
66/33kV transformer of PS1	10 (Xn)*	5	1.327
Zero-sequence generator of B10	30	5	1.318
Zero-sequence generator of PS2	30	5	1.318

Figure 11: Example of neutral earthing equipment design

But having a good design does not mean the system will work properly especially in case of failure. Therefore, to limit the potential issues, a back-up of earthing transformer has been installed in different substation to ensure a correct operation even if one earthing transformer is unavailable. This additional earthing transformer also allows to split the electrical network and continue to operate via the other sources such as the Grids or PV/BESS which could supply part of the network, always by keeping a correct grounding of the systems.

C. *Electrical protection system*

The electrical protection system is a key element in an electrical system for the safety of people and goods. The principal function is to detect any fault type (phase to phase faults, phase to earth faults, specific faults for equipment. The secondary function, if possible, is to clear only the shortest faulty part of the circuit.

For phase-to-phase faults, the system relies on cable differential protections (ANSI 87L). Each long cable is therefore selective by nature. Back-up protections are ensured by overcurrent protections (ANSI 50/51). To ensure the protection coordination, logic selectivity by using GOOSE system between protection relays is implemented reducing considerably the tripping time.

For phase-to-earth faults, the differential protection could not be enough sensitive to detect the earth faults as the neutral earthing system is impedant. Hence, the phase to earth protection plan is based on directional neutral overcurrent protection (ANSI 67N). As described in the previous chapter, the phase angle between upstream & downstream faults are enough different to set a protection threshold allowing the discrimination. Logic coordination has also been implemented to reduce the tripping time.

And finally, some specific protection functions have been implemented to protect the different equipment such as transformer thermal protection, (ANSI 49RMS). Here-below is an example of protection plan for phase to earth fault for one section.

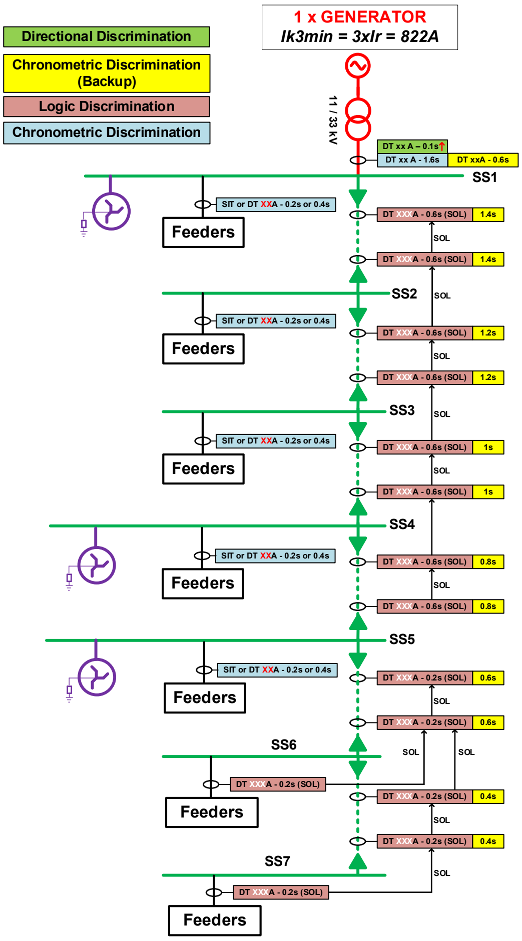

Figure 12: Example of phase to earth protection plan.

D. *Frequency, Voltage & reactive power controls*

There are two completely different systems depending on the sections. Indeed, at section 1, the system is fed from the Central Process Facility and/or the 132kV Grid connection. The sections 2, 3 and 4 are fed either by the crude oil generators, or via the Grid and PV or BESS. In this article, both types are analyzed. The main constraint regarding the voltage is to maintain the voltage variation range between +/- 10% at all substations and voltage levels but there also constraints on the reactive power levels injected on the grids.

Regarding section 1, there is 66kV substation hub where all sources are connected. The operating configurations are multiple, with/without the Grid, with/without the CPFs. In case the 66kV hub is connected to the Grid, the frequency is imposed by the national Grid. At the opposite, when there is no grid, the frequency shall be maintained by the turbo generators of the CPFs. For that, they are operating in droop mode. The interest of the droop mode is that the power can be shared among the different generators, and its robustness is proved especially in case of load variation. The main inconvenient of the droop is the frequency deviation. However, a main controller located at the 66kV hub will detect this deviation and send correction order to the CPFs through fiber optic. The turbo generators and their governors will correct their setpoints to bring back the system at 50Hz.

One of the main constraints in the 66kV hub is to limit the reactive power flowing in the 100km 66kV cables between the hub and the CPF due to the limited ampacity of the cable. 66kV variable shunt reactors have been sized and installed at 66kV Hub and at each CPF. Their CPF shunt reactors' objective is to compensate half of the reactive power generated by the 66kV cables. The 66kV variable shunt reactor's function is to compensate the reactive power coming back to the 132 kV grid if connected, or to maintain the 66kV voltage in the substation hub when not connected. The internal voltages of the CPFs are done with their step-down transformers and their OLTCs. Finally, the reactive power flow in the step-down transformer is also controlled by the turbo generators and their AVRs (Automatic Voltage Controllers).

The ECS (Electrical Control System) at the 66kV hub is the master controller and give commands to the other systems for frequency controls. For the voltage and reactive power, all controls are local and are done by the local EMS/ECS. The below figure summarizes the different controls for the 66kV hub.

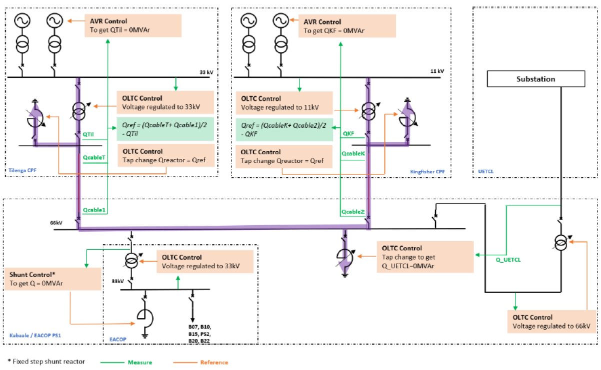

Figure 13: Voltage & Reactive power controls – 66kV hub

For the other sections (section 2, 3 and 4), first, there is the frequency to be controlled. The control for islanded system is done by the crude oil generators themselves. In case of grid connection, there is no more control, frequency is maintained by the grid. The other control regards the 33kV voltage.

The substation where a source is connected (the Crude Oil Generators or the Grid) maintains their substations at 1 p.u. – by the Automatic Voltage Regulator of the generators, by an OLTC (On Load Tap changer) associated to the transformer. For the other substations, the voltage will be controlled by switching on/off the 33kV shunt reactors. A deadband is set at +8%, -6%, and if the voltage is above (respective below) the target during a certain time at one or several substations, the ECS will switch on (or off) the shunt reactor at the substation with highest voltage deviation.

Power system studies have been performed to validate this concept. Moreover, to avoid any frequent switching, timers & hysteresis curves have been implemented after a shunt reactor switching.

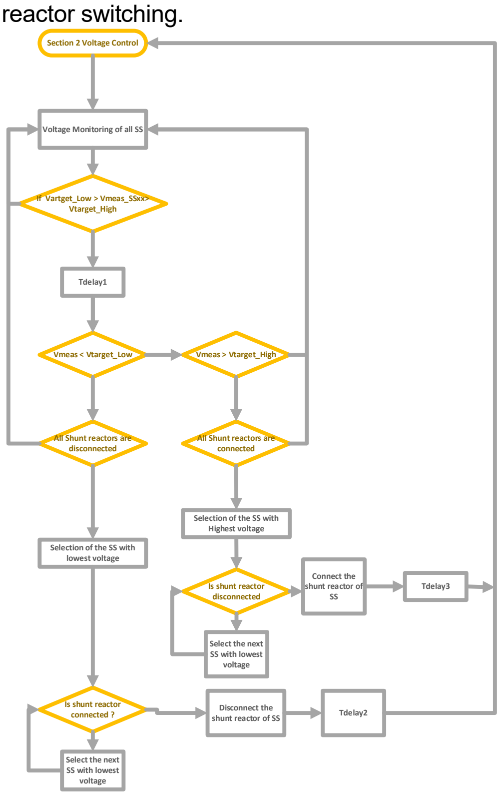

Figure 14: 33kV voltage control – principles.

In parallel to the voltage control, reactive power control shall also be implemented for two main purposes: one for grid connection with no/few reactive power feedback allowed, and the second to avoid the crude oil generators to absorb reactive powers, and thus to be closed to the generator static stability limit.

The solution was to use a single or dual shunt reactor controlled by ECS to maintain the reactive power within a range. This is an economic solution compared to variable shunt reactors or the use of Statcom. The main drawback of this solution is its inaccuracy (refer to below graph). However, grid requirements were not demanding and single shunt reactors for generators were enough.

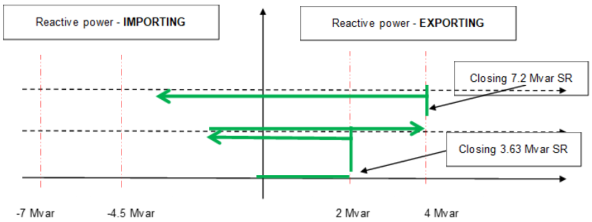

Figure 15: Reactive power control – system accuracy

E. *33kV cable and transformer energization*

One other challenge to consider is the energization of the 50km 33kV cables & the different transformers. Indeed, the power supply is via crude oil generators or Grid with very limited short circuit powers, inducing potentially a huge voltage dips for the loads.

Indeed, the loads are quite sensitive to voltage drops. In case of closing long 33kV cables or transformers in a weak circuit could lead to unacceptable voltage drops. Therefore, it has been studied the minimum number of generators in operation to have a correct energization of cables & transformers without disturbing the other subsystems. Hence, it is necessary to evaluate the risks by performing a transient analysis.

The model shall include transformer saturation to get the proper transformer inrush currents and sympathetic currents and 33kV cables. Generators are also included with their controls (speed governor & automatic voltage regulator). Accurate cable modeling represents a critical parameter in such studies, as the distributed electrical parameters and frequency-dependent behavior of cables directly govern the magnitude and dynamics of transient overvoltages.

For the analysis of cable and transformer energization, the ATP/EMTP software is widely recognized as a benchmark tool for simulating these complex phenomena.

Then, simulations are performed to evaluate the voltage dips at the different substations, generators dynamic behavior, frequency, and the correct transformer energization in the objective to define the constraints on the numbers of generators to be in operation.

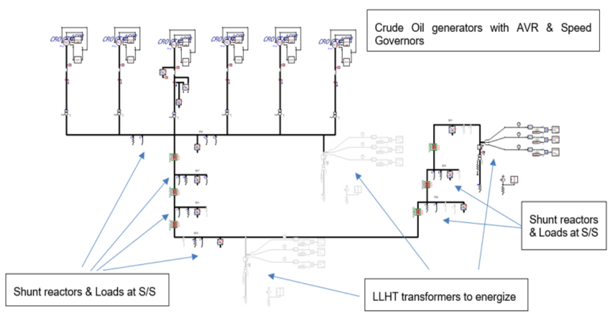

Figure 16: ATP transient model

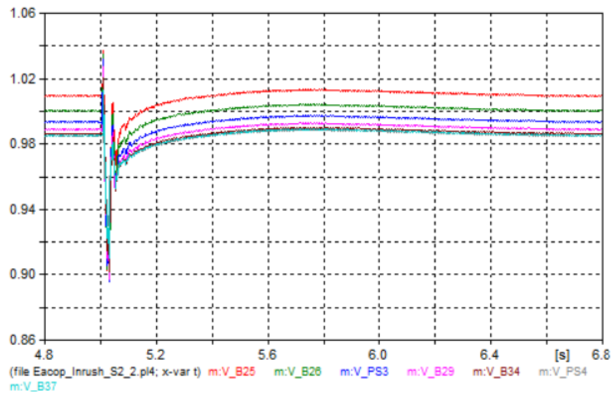

Figure 17: Example of results during transformer energization - Voltage dips

As outcome, there is no specific constraint on the number of generators to be implemented in the ECS system to authorize the transformer or cable energization.

F. *Harmonics*

The harmonics could also be a challenge. Indeed, due the long cable length in the 33kV system, there will be resonance in the electrical network, as shown in the below graphic.

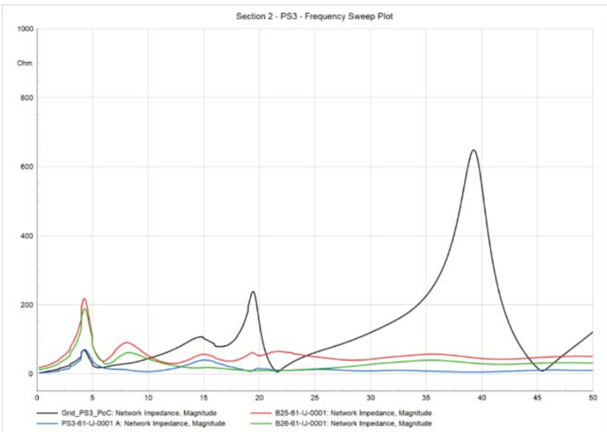

Figure 18: System impedance versus frequency.

Hence, as seen in the chart, there are several resonances. In case harmonic currents are present at these ranks, it could be an issue in the system. Therefore, it has been evaluated the harmonic distortion & spectrum on the system.

The harmonic sources are, however, limited to some few equipment such as LV electronic devices (inverters, chargers…) and in 33kV side, pumps motors are equipped with Variable Speed Drive. The technology of the VSD is 48 pulses. This means that harmonic currents are very limited and low, up to the 47^{th} rank.

The below chart shows the harmonic content at 33kV substation level compared to IEC 61000-2-4 limits.

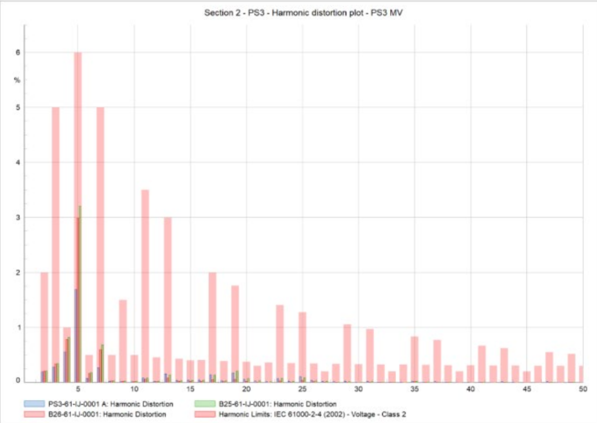

Figure 19: Voltage Harmonic content in 33kV substation

The total distortion rate in voltage (THDu) is limited and does not exceed 3% and individual harmonics are also below the IEC limits. Consequently, there is no need to install any harmonic filtering solution.

III. CONCLUSIONS

This paper highlights the different challenges the project faced during its design stages. Indeed, most of the constraints are due to long 33kV cable length. In this particular and untypical electrical network, the Engineers shall break the wall and do not think as usual as for a normal plant. The first step is to evaluate the risks & constraints for the ongoing project by performing dedicated power system studies such as short circuit current, load flow & harmonic and then all dynamic & transient analysis.

Some standards such as IEC 60071, IEC 61000, IEEE C62.92.1-, IEC 62271… could give advice & recommendations in methodology & results to achieve.

Once the analysis is done, and some issues are highlighted, it must be solved / damped but in keeping in mind to be easy to operate & maintain, reliable, and of course cost-effective.

VI. REFERENCES

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IV. VITA

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