VSD OUTPUT VOLTAGE ONLINE COMPENSATION FOR PROPER ADJUSTMENT OF ESP AT THE BEST EFFICIENCY POINT

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Abstract - Tracking the Best Efficiency Point for Electrical Submersible Pumps (ESP) applied to Oil & Gas application is imperative for improving the productivity of the whole system. The Variable Speed Drive (VSD) has a fundamental role in this operation since it is the component that provides the online adjustment of the output voltage applied to the ESP through the long cables between them. The long cables between VSD and ESP, for example the umbilical cable, could be a few up to dozens of kilometers and its electrical characteristics (mH/km, uF/km, and mΩ/km) are not neglectable, which could bring some operation concerns when adjusting the VSD output voltage.
Therefore, this paper analyses the impact on the stability of the system during the output VSD voltage adjustment taking into consideration the electrical characteristics of the cables, also simulation and experimental results, taken with a scaled prototype and a Medium Voltage VSD, of two different output VSD voltage adjustment methods are presented and analyzed.

Index Terms — ESP online adjustment, Best Efficiency Point tracking, Variable Speed Drive.

I. INTRODUCTION

Variable Speed Drives (VSD) are widely applied in Oil & Gas industry for driving Electrical Submersible Pumps (ESP). The use of VSDs for such Oil & Gas applications overcomes a series of difficulties, such as, voltage drop related to long cables between the power supply and the ESP itself, speed adjustment for optimized production control and others. Figure 1 presents the single line diagram of a VSD driving an ESP in a standard Oil & Gas application.

One of the requirements of this application is to allow the track of the Best Efficiency Point (BEP) of the ESP and for that, sometimes, it is necessary to adjust the VSD output voltage during operation. As usually the VSD control just allows the operator to adjust the output voltage by adjusting the u/f curve, it means, changing the output speed, the tracking of the BEP turns into a complex and time-consuming task, since the operator must stop the equipment and the process, to perform the VSD output voltage necessary compensation.

The main reason the VSD control does not allow the online changing of output voltage is related to disturbances that would happens, mainly on the ESP magnetic flux and consequently on the ESP current.

To solve this issue, this paper presents an alternative technique to perform the VSD output voltage regulation without causing any disturbance or instability on the ESP electrical variables.

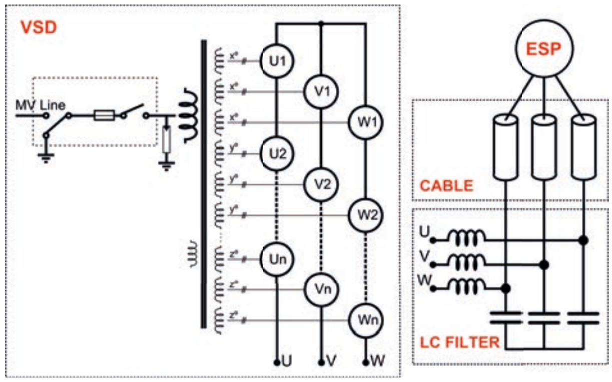


Fig. 1 Single line diagram of a standard ESP application.

Such changes during ESP operation are important since the main parameters used to calculate the pump curve and the BEP, such as Base Sediment and Water (BSW), bubble point, reservoir pressure, ESP back pressure and other topside restrictions, such as booster pumps operational curves, header pressure, and flowlines capacity, etc.

Considering the production of a single well, each hour stopped to perform such adjustments could represent a considerable reduction of a field production, and those adjustments are frequent during special operational conditions, such as well clean-up.

Intervention in the well is complex and costly, due to that, the integrity of ESP is a particularly important factor to be considered, so both Mean Time Between Failure (MTBF) and BEP are important factors to be considered during the lifetime of each ESP [1], [2].

II. VOLTAGE ADJUSTMENT IN OPERATION

A. Simulation analyses

The concern about the impact of adjusting the output voltage during operation is initially verified by means of a computational simulation using PSIM®. Figure 2 presents the traditional control scheme of a VSD where a fixed u/f curve is applied to determine the modulation index to modulate the output voltage [3]. Figure 3 presents the simulated circuit that imposes the u/f curve to an induction motor load. The simulation was taken considering two different scenarios, the motor directly connected to VSD output or connected through a sinus filters (low pass LC filter) plus 1km of umbilical cable, the cable is modeled in the simulation by a π filter, as can be seen in Figure 4.

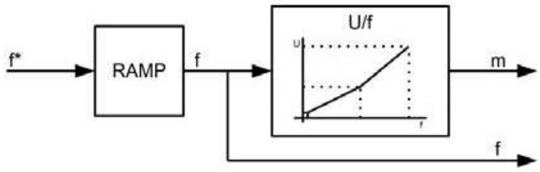


Fig. 2 Scalar control u/f curve.

The output voltage variation is applied through a multiplication factor to the modulation index. Two methods are verified by simulation. The first method adjusts the output VSD voltage by a voltage step, not considering the voltage step magnitude. That is the most common method found in VSDs available in the market.

The second method makes use of a first order low pass filter to adjust the modulation index and consequently the output voltage VSD imposed to motor.

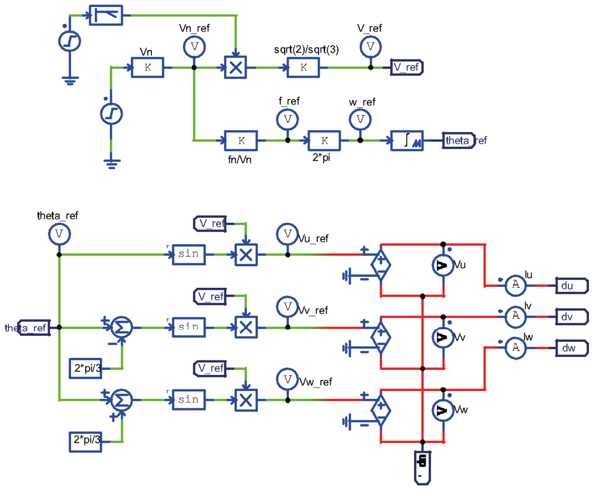


Fig 3. Simulated circuit to verify the effect of adjusting the output voltage of an induction motor during operation.

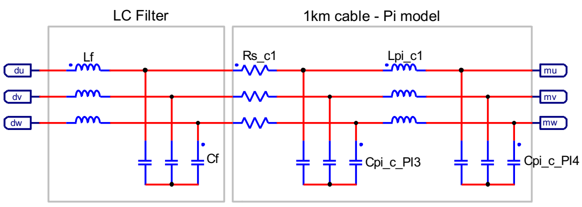


Fig 4. LC filter and π filter model, representing a motor cable of 1km.

Figure 5, Figure 6, Figure 7 and Figure 8 shows the torque ripple as a consequence of the voltage adjustment by both methods, step and filtered voltage adjustment, with and without cables + sinus filter. The results are summarized in Table I, where it is possible to observe that filtered voltage variation drastically decreases the torque ripple produced by the induction motor.

TABLE I
MOTOR RESPONSE FOR A VOLTAGE VARIATION FROM 682V TO 745V

Method	Motor connection	Torque Ripple	Figure
Step	Direct	79 Nm	3
Step	Cable + filter	36 Nm	4
Filter	Direct	1.3 Nm	5
Filter	Cable + filter	0.6 Nm	6

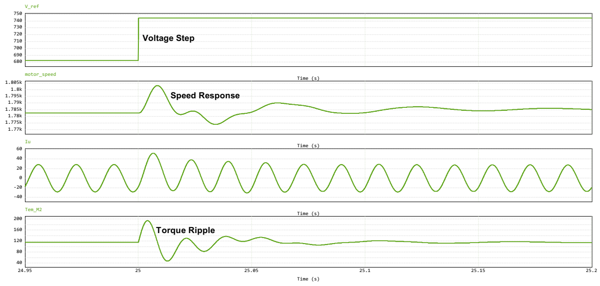


Fig 5. Step variation of modulation index (682V to 745V) without cables and sinus filter. 79Nm of torque ripple related to a 115Nm nominal load torque.

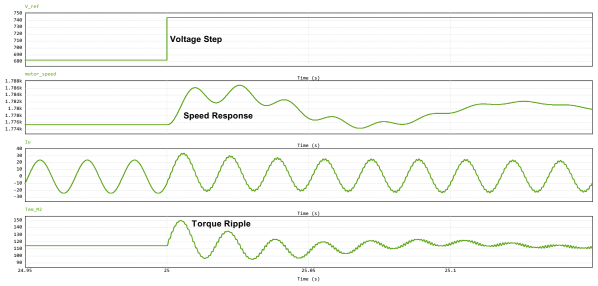


Fig 6. Step variation of modulation index (682V to 745V) with cables and sinus filter. 36Nm of torque ripple related to a 115Nm nominal load torque.

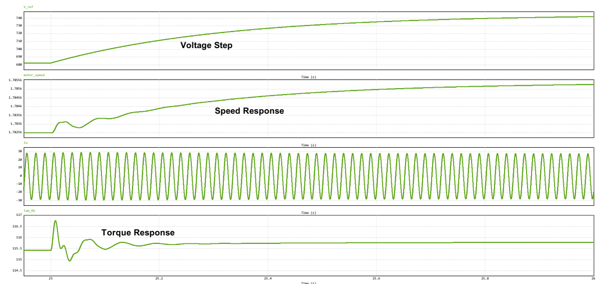


Fig 7. Filtered variation (Tc = 0.5s) of modulation index (682V to 745V) without cables and sinus filter. Neglectable torque ripple of 1.3Nm.

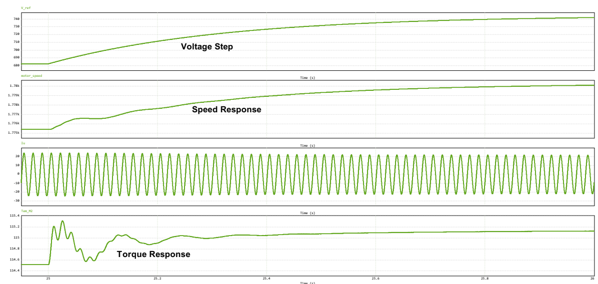


Fig 8. Filtered variation (Tc = 0.5s) of modulation index (682V to 745V) with cables and sinus filter. Neglectable torque ripple of 0.6Nm.

The variation of the motor voltage amplitude takes to electromagnetic flux variation. For induction motors, the variation takes to a slightly speed motor correction.

Also, the above results show that even using the step method, the presence of the cable+filter between the drive and motor, helps to reduce by half the disturbance in ESP toque.

B. Implementation

Different from the control scheme of Figure 2, where the modulation index is defined by a fixed u/f curve, the proposed implementation of the control system is done applying first order filters on the parameters of an adjustable u/f curve, as presented in Figure 9.

The adjustable u/f curve is defined by a combination of 5 different parameters, 3 of them defining the voltage levels of maximum voltage (V_{MAX}), intermediate voltage (V_{INT}) and voltage at 3Hz (V_{3HZ}). The last two parameters define the frequency related to the maximum voltage (f_{FW}) and the frequency related to the intermediate voltage (f_{INT}).

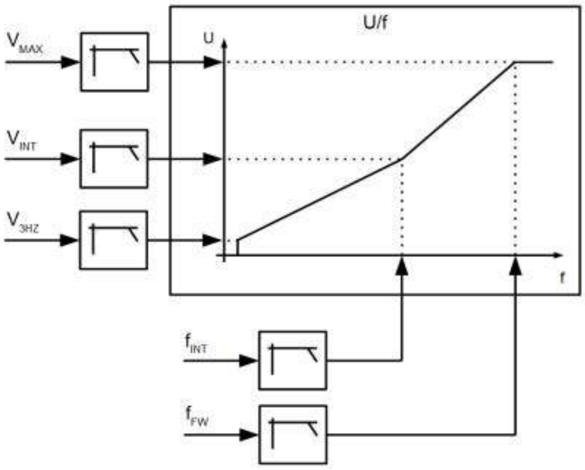


Fig 9. Implementation of online adjustment of u/f curve.

C. Scaled Low Voltage Validation

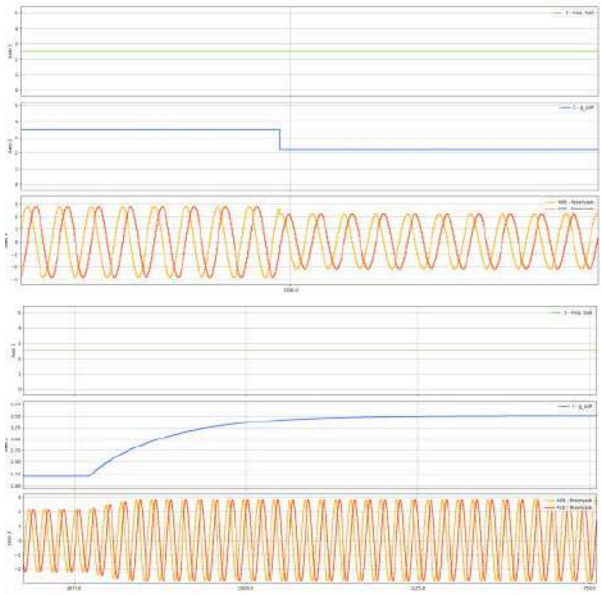
A low voltage bench validation test is performed, without load applied to the induction motor, to observe the influence of the u/f curve modification on the modulation index and the imposed voltage by the modulator when the occurrence of a voltage step variation and when the occurrence of a variation through the low-pass filter, as presented in Figure 10.

The test results presented below are performed using a Low Voltage Prototype (LVP), connected to a 760V, 30kW, 1800 rpm, 60Hz induction motor.

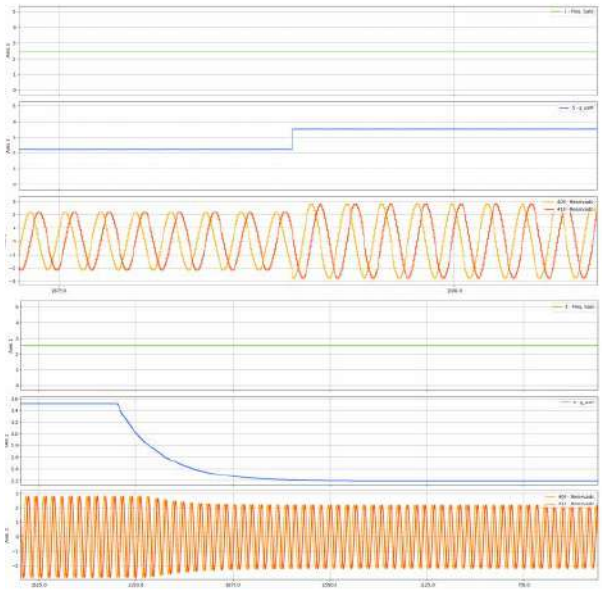
For the first tests (Figure 11, Figure 12, Figure 13, and Figure 14), the speed reference (green line) is adjusted to 1600rpm, and the output voltage reference (blue line) is adjusted as indicated in the figure’s subtitle.

The orange waveforms represent the output current of the VSD, what gives the idea of how the motor torque oscillation during the imposed transitions is.

The bottom blue and green waveforms are alpha and beta components of the VSD’s output voltage.



(a)



(b)

Fig 10. Bench test. Green line: output frequency. Blue line: modulation index. Yellow line: alpha voltage produced by the modulator. Orange line: beta voltage produced by the modulator.

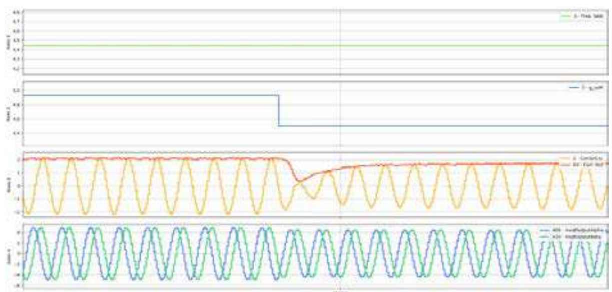


Fig 11. Output voltage reference adjusted from 100% to 90%, step variation. Motor speed at 1600rpm without load.

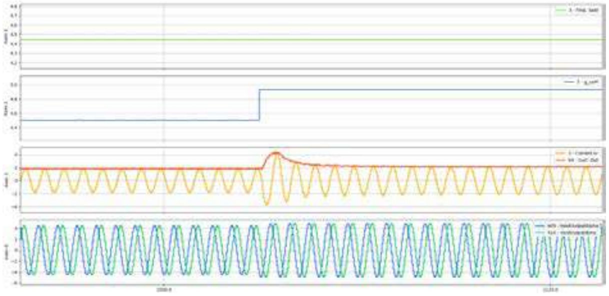


Fig 12. Output voltage reference adjusted from 90% to 100%, step variation. Motor speed at 1600rpm without load.

Fig 13. Output voltage reference adjusted from 100% to 90%, with low pass filter. Motor speed at 1600rpm without load.

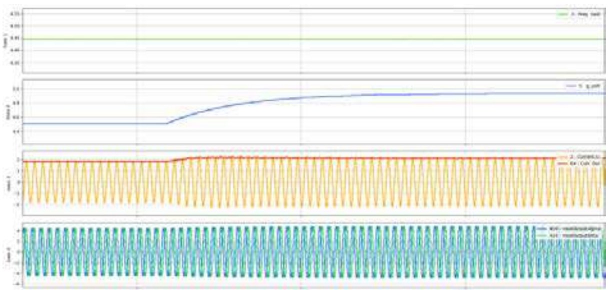


Fig 14. Output voltage reference adjusted from 90% to 100%, with low pass filter. Motor speed at 1600rpm without load.

From figures 11 to 14 is possible to verify that even with a step voltage variation there is no significant torque oscillation, mainly because of the absence of load connected to the motor.

The next figures present the results with induction motor operating at 55% of nominal load, that is the maximum load capacity available in the LV test bench. Figure 15 and figure 16 presents the step variation test results and Figure 17 and Figure 18 presents the filtered variation result.

For both situations, with and without load imposed to the LV induction motor, is verified similar results, where the step adjustment of the modulation index takes to a significant current ripple, while a filtered adjustment of the modulation index takes to a neglectable load current variation, and consequently neglectable motor torque oscillation.

Table II presents the current ripple for each tested configuration. The current ripple represents the difference between the initial value and the transient value reached as a percentage of the VSD nominal current.

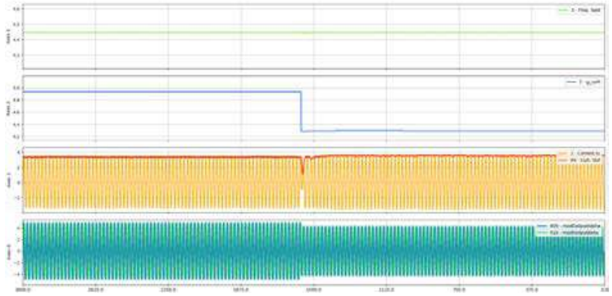


Fig 15. Output voltage reference adjusted from 100% to 85% by a step variation. Motor speed at 1600rpm under 55% of load.

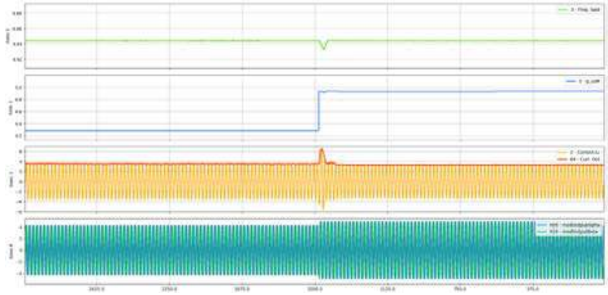


Fig 16. Output voltage reference adjusted from 85% to 100% by a step variation. Motor speed at 1600rpm under 55% of load.

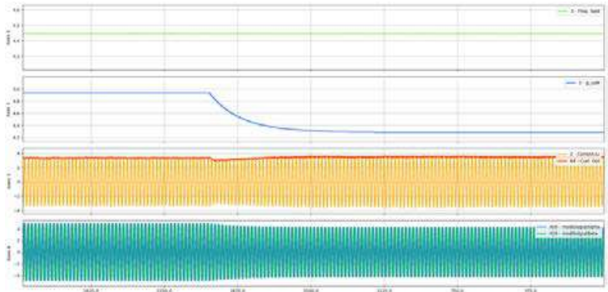


Fig 17. Output voltage reference adjusted from 100% to 85%, with low pass filter. Motor speed at 1600rpm under 55% of load.

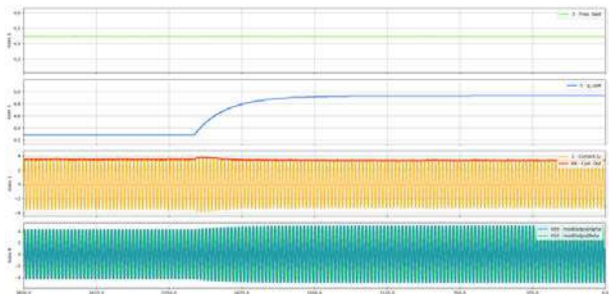


Fig 18. Output voltage reference adjusted from 85% to 100%, with low pass filter. Motor speed at 1600rpm under 55% of load.

For the cases with filtered variations of the modulation index the current ripple is considered neglectable, as the values are extremely low in comparison to the values presented during step variations, besides that, these small variations happen in a period that indicates to be related to the dynamics of the machine flux variations.

TABLE II
CURRENT RIPPLE FOR LVP TESTS WITH MOTOR

Figure	Initial voltage	Final voltage	Current Ripple
11	90%	100%	-33%
12	100%	90%	48%
13	90%	100%	-
14	100%	90%	-
15	100%	85%	-44%
16	85%	100%	54%
17	100%	85%	-
18	85%	100%	-

III. EXPERIMENTAL RESULTS

The experimental results are taken during a load test of a Medium Voltage (MV) VSD driving a MV induction motor, Figure 20. The main features of the MV VSD are:

- Input voltage: 4160V
- Input transformer: Integrated 24 pulse
- Output voltage: 4160V
- Output current: 70A
- Output power: 500kVA
- Total number of cells: 12
- Control mode: Scalar
- Motor type: 4 poles Induction motor

The main purpose of the experimental tests is to validate the simulation analyses under the same output voltage variation conditions, from 90% to 100% and from 100% to 90%. The MV VSD applied to the experimental test does not have an output LC filter and cable with considerable length between the VSD and motor, for that reason just the direct connection analyses can be validated.

The above-mentioned variation conditions are applied to the VSD modulation index adjustment by a step variation and by using a low pass filter (cutoff frequency of 1Hz).

The next figures present the output voltage and current measurements during the modulation index (output voltage) variation, where is possible to see the output voltage adjustment and the consequent load current response. For experimental tests it is not possible to directly measure the motor torque, but the measured load current is considered directly proportional to the motor torque.

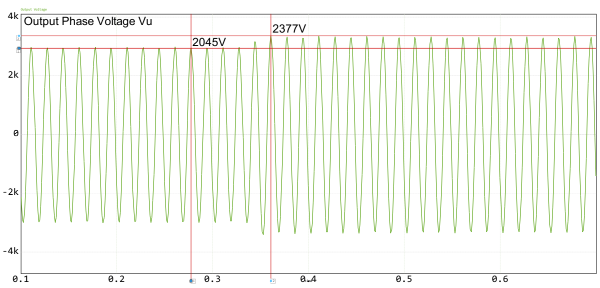


Fig 19. Voltage measurement: Output voltage reference adjusted from 90% to 100%, without low pass filter (step). Motor speed at 1800rpm under 100% of load.

Fig 20. 70A/4160V Medium voltage Drive.

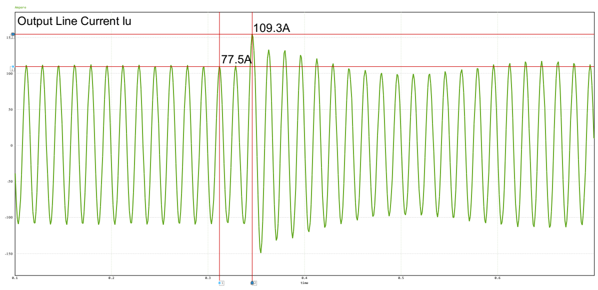


Fig 21. Current measurement: Output voltage reference adjusted from 90% to 100%, without low pass filter (step). Motor speed at 1800rpm under 100% of load.

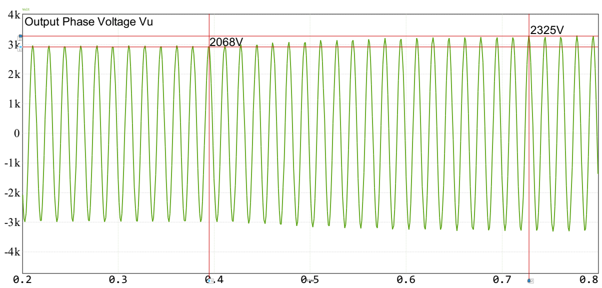


Fig 22. Voltage measurement: Output voltage reference adjusted from 90% to 100%, with low pass filter. Motor speed at 1800rpm under 100% of load.

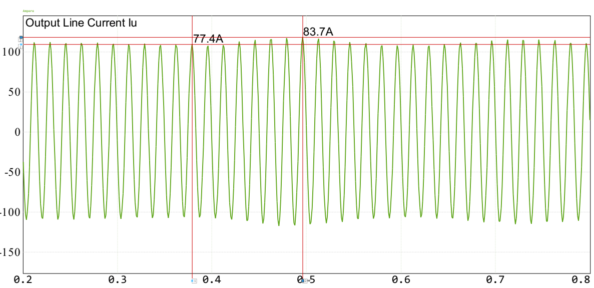


Fig 23. Current measurement: Output voltage reference adjusted from 90% to 100%, with low pass filter. Motor speed at 1800rpm under 100% of load.

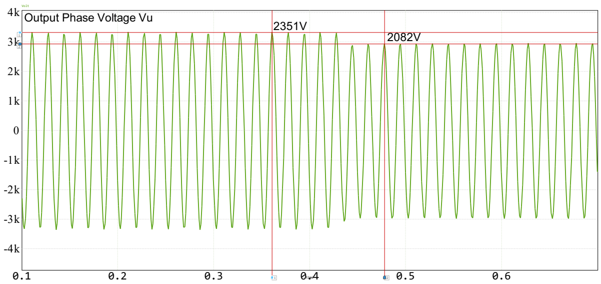


Fig 24. Voltage measurement: Output voltage reference adjusted from 100% to 90%, without low pass filter (step). Motor speed at 1800rpm under 100% of load.

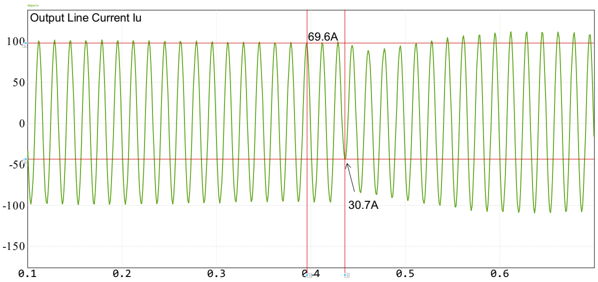


Fig 25. Current measurement: Output voltage reference adjusted from 100% to 90%, without low pass filter (step). Motor speed at 1800rpm under 100% of load.

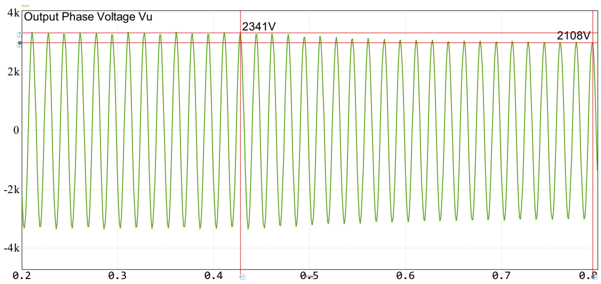


Fig 26. Voltage measurement: Output voltage reference adjusted from 100% to 90%, with low pass filter. Motor speed at 1800rpm under 100% of load.

Table III summarizes the results for both methods, step and filtered adjustments, when a variation from 90% to 100% is imposed to the output voltage.

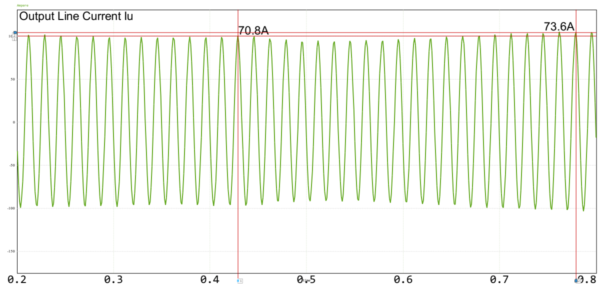


Fig 27. Current measurement: Output voltage reference adjusted from 100% to 90%, with low pass filter. Motor speed at 1800rpm under 100% of load.

TABLE III
MOTOR RESPONSE FOR A VOLTAGE VARIATION FROM 3745V TO 4160V

Method	Motor connection	Current Ripple	Figure
Step	Direct	31.8A	19, 20
Step	Cable + filter		
Filter	Direct	6.3A	21, 22
Filter	Cable + filter		

Table IV summarizes the results for step and filtered adjustments when a variation from 100% to 90% is imposed to the output voltage.

TABLE IV
MOTOR RESPONSE FOR A VOLTAGE VARIATION FROM 4160V TO 3745V

Method	Motor connection	Current Ripple	Figure
Step	Direct	38.9A	23, 24
Step	Cable + filter		
Filter	Direct	2.8A	25, 26
Filter	Cable + filter		

IV. CONCLUSIONS

The capability of changing the operational parameters during ESP operation reduces the production losses, allow often and optimal adjustments, increasing production and reducing the number of maneuvers of each pump also helps to increase the MTBF.

The filtered adjustment of the u/f curve parameters allows the ESP applied voltage to be adjusted in a smooth way, avoiding the occurrence of any current disturbances related to the ESP dynamics and also cables and filters.

By simulation it is possible to direct observe the effect on the electromagnetic motor torque caused by the VSD output voltage adjustment, besides that through practical experiments a similar behavior can be observed on VSD total output current, validating the simulation results.

V. REFERENCES

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