ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering
Tome XX [2022] | Fascicule 4 [November]

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ANALYSIS OF CONTROL MODES IMPLEMENTED IN VVVF CONVERTERS FROM THE ASPECT OF INCREASING ENERGY EFFICIENCY

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Abstract: In hydraulic systems such as those with centrifugal pumps, VVVF converters are widely used to control flow and pressure. The aim of this paper is to show that proper power drive control mode can increase the energy efficiency of the overall system. For the realization of this research, an experimental setup was used, which consists of two separate centrifugal pump-based systems. Each system consists of: centrifugal pump, frequency (VVVF) converter, command table, pressure sensor, flow sensor, manometer and rotameter. Using manual valves, it is possible to achieve higher value of pressure or flow. A comparison of the efficiency of different control types of both converters was performed, and Schneider Electric Altivar ATV630U07N4 and ATV320U06M2C frequency converters were used. Measurements of electricity consumption were performed for several cases of system settings for U/F Standard, U/F Quadratic, U/F Energy Saving and Sensorless Vector Control mode of electric motor control. At the end, the measurement results were presented and as well as comparisons of the efficiency between two converters.
Keywords: hydraulic systems, centrifugal pumps, VVVF converters, energy efficiency, experimental setup

1. INTRODUCTION

Electric motor systems in industrial and infrastructural applications with pumps, fans and compressors in buildings are responsible for 53% of total world electricity consumption, according to the International Energy Agency (IEA) [1]. Electric motor consumption can be reduced by up to 60% by using frequency converters. In addition to reduce electricity consumption, the use of frequency converters reduces maintenance costs and improves control and reliability of the process [2].

That savings of up to 60% can be achieved was proven in a study conducted in 2018 in Saudi Arabia. The research consisted of measuring electricity consumption for two different air conditioning systems. The first system was a conventional ON/OFF system, and the second air conditioning system was with a built-in frequency converter and PID controller, and they were used to control the climate compressor. Electricity savings for hot and humid days in the summer season, when the demand for cooling is very high, amounted to 20%, and the savings were achieved with the second system. For days that are not so warm, savings of 22-50% were achieved [3].

In addition to saving electricity, frequency converters can lead to other savings in industrial applications. In a study conducted in 2019 at a sugar factory in Ethiopia, the frequency converter led to savings in electricity, savings in fuel used for combustion in a thermal power plant and to a reduction in CO2 emissions. The sugar factory, in which the research was conducted, has a thermal power plant that produces electricity only for the needs of the factory. The thermal power plant uses a centrifugal fan to draw air for combustion into the burners and to extract the combustion products from the furnace. The combustion rate in the thermal power plant is controlled by a centrifugal fan, and instead of the classical system, a frequency converter was used to drive the electric motor of the fan. With such a configuration, the 400 HP centrifugal fan motor consumed 471362.77 kWh less electricity per year, and the thermal power plant consumed 1885.45 tons less fuel used for combustion and electricity production. Lower fuel consumption lowered the CO2 emissions. This was all achieved with a frequency converter that allowed the process of combustion and electricity production to be adapted to the needs of the factory [4].

Over the years, various control algorithms of VVVF converters have been developed, and with their application even greater energy savings can be achieved. In the research conducted in 2018, a comparison of the efficiency of different ways of controlling of an electric motor was conducted. Measurements of electricity consumption were performed for U/F Standard, U/F Quadratic, U/F Energy Saving and Direct Vector Control, and a 20 HP, 480 V, 60 Hz fan driven system was used for the research. Consumption of U/F Standard mode was taken as the reference model, and the consumptions of other modes were presented in relation to the reference model. At an operating frequency of 30 Hz, direct vector control is 10% more efficient, U/F Quadratic 13%, and U/F Energy Saving 14% compared to the U/F Standard. At 40 Hz direct vector control is 3% more efficient, U/F Quadratic 4% and U/F Energy Saving 5%, and at 50 Hz vector control is 1% more efficient, U/F Quadratic 2% and U/F Energy Saving 3%. No PID controller was used in the system and measurements were performed for the same load [5]. After falling by 1.1% in 2020 due to the impact of the Covid-19 pandemic, according to the International Energy Agency, global electricity demand grew by 6% in 2021. This was the largest annual increase in absolute terms (1500 TWh) and the largest percentage growth since 2010, after the financial crisis. The total electricity consumption in 2019 in the world was 23432 TWh, in 2020 23177 TWh, and in 2021 about 24677 TWh. In 2022, electricity demand is expected to grow by 3% [6].

Global demand for electricity is growing faster than renewable energy sources, leading to a sharp increase in fossil fuel production. Because of that, in 2021, there was an increase in carbon dioxide emissions, close to 7%, which led to a record level [6, 7].

In 2021, coal has satisfied more than half of the increase of global electricity demand. Coal electricity production peaked by 9%. Renewable energy sources increased by 6%, gas production increased by 2%, while nuclear energy increased by 3.5%, almost reaching the 2019 level. Increased demand for fossil fuels combined with supply constraints has resulted in shortages and high electricity and fuel prices. Average wholesale electricity prices in the fourth quarter of 2021 were four times higher than their average in the period 2015-2020. The average world price of electricity, in December 2021, was 0.137 US dollars per kWhr for household users and 0.125 US dollars per kWhr for business users [6, 8].

The aim of this research was to investigate and determine whether different modes of controlling the pump drive can affect and how much the increase of the energy efficiency of the overall system. Also, two different VVVF converters from the same manufacturer Schneider Electric were used and compared. The first is intended for pump and fan drives (Altivar ATV630U07N4), and the second for machine drives (ATV320U06M2C).

The paper is structured so that the second chapter describes the experimental equipment used for research, and the rest of the paper describes the results of energy consumption and comparison of the efficiency of different control modes of both frequency converters. Measurements were performed for three cases of system setup for U/F Standard, U/F Quadratic, U/F Energy Saving and Sensorless Vector Control modes of electric motor control. In each of the three cases, the most efficient mode of controlling of each frequency converter was determined and a comparison of efficiency of control modes between two used converters were performed.

2. DESCRIPTION OF THE EXPERIMENTAL SETUP

For the realization of this research, an experimental setup was used, which consists of two separate systems, and each system consists of: a pump, a frequency converter, a command table, pressure and flow sensors, rotameter and manometer (Fig. 1). The command tables are used to control the frequency converters, and it is possible to maintain the defined pressure or flow value in the system.

The experimental setup drive system consists of (Fig. 1): Schneider Electric Altivar ATV630 and ATV320 frequency converters and Pedrollo PK65 centrifugal water pumps. Using manual valves, it is possible to simulate the change of suction depth and the maximum head of both pumps independently.

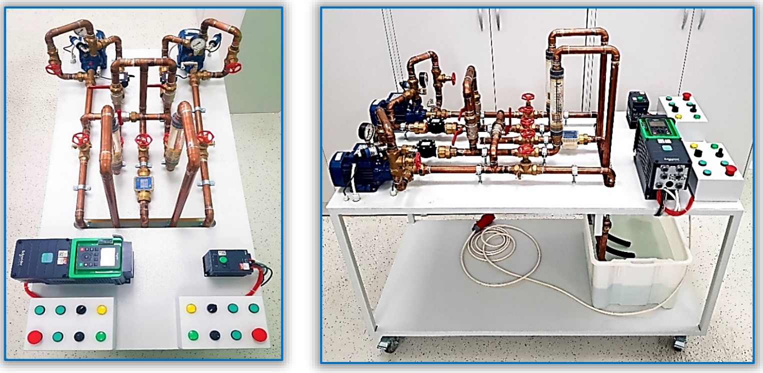

Figure 1. Experimental setup

— Frequency converter ATV630

The model of one of the two VVVF converters built into the experimental setup is the Altivar ATV630. ATV630 is connected to a three-phase power supply, 380 V, 50 Hz. The power of the electric motor of the water pump is 0.5 kW, and the power of the ATV630 is 0.75 kW [9].

ATV630 has 4 U/f control modes, and they are [10, 11]:

≡ U/F Standard, standard motor control mode. Used for applications that do not require high performance;
≡ U/F 5pts, the same control mode as the previous one with predefined 5 operating points of the motor. Suitable for avoiding a resonance;
≡ U/F Quadratic, control mode in which the voltage-frequency ratio is not linear, as in standard mode (U/f), but U/f^2 ratio. Control mode intended for variable torque applications and commonly used for pumps and fans;
≡ U/F Energy Saving, a control mode that also uses the U/f^2 ratio. Mode that reduces motor current when motor load is reduced while preserving drive performance up to full load.

— Frequency converter ATV320

ATV320 frequency converter is used to control the second pump. ATV320 is connected to a single-phase power supply, 220 V, 50 Hz. The power of the electric motor of the water pump is 0.5 kW, and the power of the ATV320 is 0.55 kW [12]. The ATV320 implements four U/f control modes and they are the same as the ATV630 control modes. In addition to scalar (U/f) control mode, ATV320 also has indirect vector control mode (Sensorless Vector Control, SVC) which is used for the cases when high performance is required during startup or operation of the drive [10, 13, 14].

— Pedrollo PK65 centrifugal water pump

Two centrifugal pumps manufactured by Pedrollo PK65 were installed on the experimental setup. The hydraulic characteristics of the Pedrolo PK65 pump are [15]: flow: 5 - 50 L/min, the maximum pump head is 55 m, the minimum pump head is 8 m, the maximum water suction depth is 8 m, the maximum operating pressure is 6 bar. The electrical characteristics of the three-phase asynchronous electric motor that drives the pump are: 50 Hz, 0.5 kW, 1.7 A/3 A, 2900 min^{-1}.

2. ANALYSIS OF DIFFERENT CONTROL MODES OF CENTRIFUGAL PUMPS FROM ASPECT OF ENERGY EFFICIENCY

ATV630 has three modes of electric motor control (U/F Standard, U/F Quadratic and U/F Energy Saving) while ATV320 in addition to the already mentioned three modes also has a vector mode of electric motor control without the use of sensors (SVC).

The research begins by measuring the electric energy consumption of the pumps motors, for all control modes of both frequency converters, for a certain time interval.

Both frequency converters have implemented the function of PI pressure regulator. The parameters of the PI controller for ATV630 are $k_p = 0.67$ and $T_i = 0.83$, and for ATV320 are $k_p = 0.25$ and $T_i = 0.83$. Potentiometers are used to set the references from 0 to 6 bar for each frequency converter separately. Closing the valve simulates an increase of pump head (simulates the change of load in the system). In order for both pumps to have the same loads during the experiments and to obtain the closest possible conditions for all measurements of pumps motor consumption, the pumps outlets are directed through the same valve.

Measurements of electric energy consumption of all control modes for both pump motors were performed for three system setup cases:

≡ for case of low flow and very low pressure in the system (case of idling with low speed),
≡ for case of high flow and very low pressure in the system (case of idling with high speed),
≡ for case of high pressure and high flow in the system (load close to nominal at high speed).

On the described way, a total of 7 measurements of electricity consumption were performed for one system adjustment. Active electric power for both motors is calculated according to:

$$P_{el}[\mathrm{W}]=\sqrt{3}UI\cdot 0.76, \tag{1}$$

where are: U pump motor supply voltage, I electric current of the pump motor and 0.76 power factor.

Pump motor current and voltage were measured during the entire measurement interval. Based on the measured values and with the help of (1), the active electrical power of the pump motor is calculated.

Based on the calculated active electric power of the motor, the electric energy consumed by the motor during the operation of ten minutes is calculated according to:

$$E_n[\mathrm{Wh}]=\sum_{0}^{600}P_{el,\,n}, \tag{2}$$

where are: E_n the amount of energy consumed by the engine during operation of n seconds and $P_{el,n}$ electrical power of the motor in the n-th second.

The hydraulic power of the pump is calculated according to:

$$N[\mathrm{W}]=p[\mathrm{bar}]\cdot 10^5\cdot Q[\mathrm{L/min}]\cdot\frac{10^{-3}}{60}, \tag{3}$$

where are: p pump outlet pressure and Q flow at the pump outlet.

3. CASE OF LOW FLOW AND VERY LOW PRESSURE IN THE SYSTEM

In the case of low flow and very low pressure, the reference value of the pressure in the system is set to 0.21 bar (Fig. 2), and the flow in the system is set to 12 L/min using a valve (Fig. 3). Based on the measured pressure and flow, using (3), the hydraulic power of the pump in the system was calculated and it is 4.2 W. The diagram of the hydraulic power is shown on Fig. 4. The values of pressure, flow and hydraulic power of the pump are the same for all 7 consumption measurements.

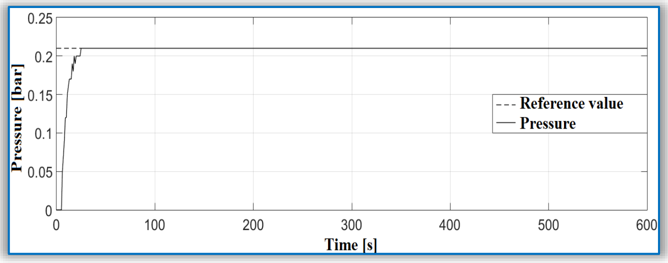

Figure 2. System pressure in case of low flow and very low pressure

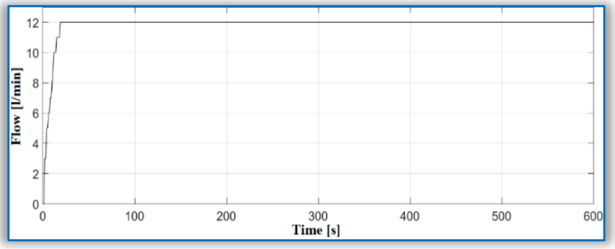

Figure 3. System flow in case of low flow and very low pressure

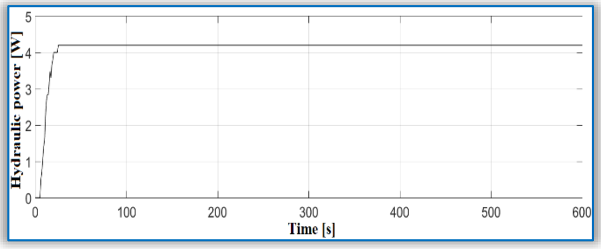

Figure 4. Hydraulic power of the pump in case of low flow and very low pressure

— Measurements of electrical quantities of ATV630 driven pump drive

After a ten minutes measurement of the motor consumption of the pump, controlled with the ATV630 frequency converter in U/F Standard control mode, diagrams of the electric current and supply voltage were obtained as on Fig. 5 and Fig. 6, respectively.

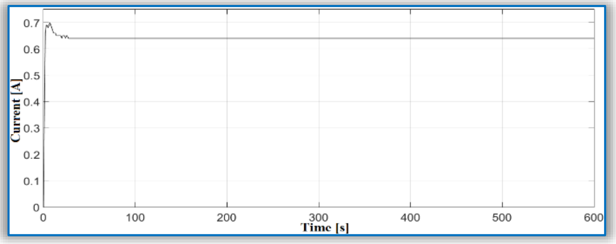

Figure 5. Pump motor current diagram in U/F Standard control mode

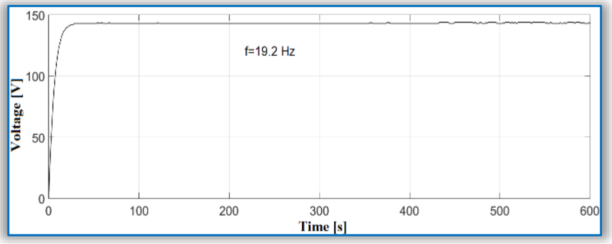

Figure 6. Pump motor voltage diagram in U/F Standard control mode

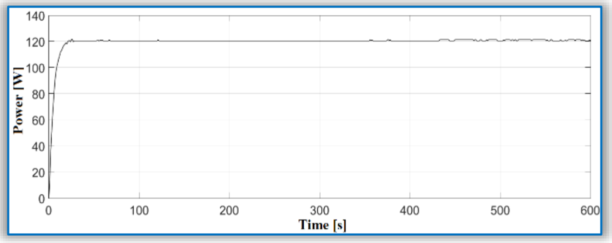

Figure 7. Diagram of the active electrical power of the pump motor in U/F Standard control mode

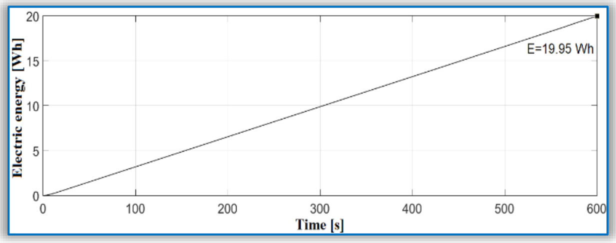

Figure 8. Pump motor electric energy consumption diagram in U/F Standard control mode

From the diagram of the pump electric current, on Fig. 5, a current overshoot is observed during start up, after which the current stabilizes and remains constant until the end of the measurement. The value of the current in the steady state is 0.64 A.

From the voltage diagram on Fig. 6, it is noted that there are no overshoots, and the voltage value is 143 V, frequency of 19.2 Hz. Based on the current and voltage, the active electric power is calculated, according to (1), and then a diagram of the same is drawn, as on Fig. 7. Based on the calculated power, using (2), the energy consumed by the engine during the ten minutes operation was calculated. The diagram of consumed electricity is shown on Fig. 8.

During 10 minutes of operation, the pump motor controlled by the ATV630 frequency converter in U/F Standard control mode consumed 19.95 Wh of electric energy in case of low flow and very low pressure. Due to space savings, further results will not be displayed graphically but only analytically and tabularly.

Of all three ATV630 frequency converter control modes for low flow and very low pressure, the pump motor consumed the least electric energy in U/F Energy Saving control mode.

Table. 1. Results of measurements of electrical quantities of ATV630 driven pump drive

Control mode	Current [A]	Voltage [V]	Freq. [Hz]	Current overshoot	El. energy [Wh]
U/F Standard	1.1	143	19.2	yes	19.95
U/F Quadratic	0.34	83	19.4	no	5.93
U/F Energy Saving	0.32	77	20.1	no	5.34

As seen from Table 1, the pump motor current was lowest in U/F Energy Saving control mode (0.32 A). When operating in U/F Standard control mode, overshoot occurs at start up, while in other control modes this was not the case. The pump motor voltage was lowest in U/F Energy Saving control mode (77 V). In none of the three control modes a voltage overshoot during start up did not occur. The electric energy consumption values of the pump motor are highest for U/F Standard control mode (19.95 Wh), followed by U/F Quadratic (5.93 Wh) and lowest for U/F Energy Saving (5.34 Wh).

— Measurements of electrical quantities of ATV320 driven pump drive

As was done for the ATV630, the same 10 minutes measurement of pump motor consumption in U/F Standard control mode was done for the ATV320. In addition, measurements were performed for the SVC control mode that the ATV630 does not have. Of all four modes of control of the ATV320 frequency regulator in case of low flow and very low pressure, the pump motor consumed the least electric energy in U/F Energy Saving control mode.

Table. 2. Results of measurements of electrical quantities of ATV320 driven pump drive

Control mode	Current [A]	Voltage [V]	Freq. [Hz]	Current overshoot	El. energy [Wh]
U/F Standard	1.1	85	20	yes	20.28
U/F Quadratic	0.6	48	21	no	6.2
U/F Energy Saving	0.6	46	20.9	no	5.95
Sensorless Vector Control	1.1	85	20	yes	20.29

As seen from Tab. 2, the electric current of the pump motor was the lowest in U/F Energy Saving and in U/F Quadratic control mode. When operating in U/F Standard and SVC control modes, an overshoot occurs at startup. The pump motor voltage was lowest in U/F Energy Saving control mode (46 V). There was no voltage overshoot during the start up in any case. Pump motor electric energy consumption values are highest for U/F Standard and SVC control modes (20.28 and 20.29 Wh, respectively), followed by U/F Quadratic (6.2 Wh) and lowest for U/F Energy Saving (5.95 Wh).

4. CASE OF HIGH FLOW AND VERY LOW PRESSURE IN THE SYSTEM

In the case of high flow and very low pressure, the reference value of the pressure in the system is set to 0.2 bar, and the flow in the system is set to 39 L/min using a valve. Based on the measured pressure and flow, the hydraulic power of the pump in the system was calculated and it is 13 W. The values of pressure, flow and hydraulic power of the pump are the same for all 7 consumption measurements.

— Measurements of electrical quantities of ATV630 driven pump drive

Of all the three modes of control of the ATV630 frequency converter in case of high flow and very low pressure, the pump motor consumed the least electric energy in U/F Energy Saving control mode.

From Tab. 3 it can be seen that the electric current of the pump motor was the lowest in the U/F Energy Saving control mode (0.48 A) and the highest in the U/F Standard control mode (0.64 A). Of all three control modes, only U/F Standard control mode had a current overshoot at startup. The pump motor voltage was the lowest in U/F Energy Saving control mode (154 V), then in U/F Quadratic (246 V), and the highest was in U/F Standard control mode (246 V), Tab. 3. In none of the three control modes a voltage overshoot during start up did not occur. Pump motor electric energy consumption values are highest for U/F Standard control mode (39 Wh), followed by U/F Quadratic (27.63 Wh) and lowest for U/F Energy Saving (15.68 Wh).

Table 3. Results of measurements of electrical quantities of ATV630 driven pump drive

Control mode	Current [A]	Voltage [V]	Freq. [Hz]	Current overshoot	El. energy [Wh]
U/F Standard	0.64	285	39.5	yes	39
U/F Quadratic	0.53	247	40	no	27.63
U/F Energy Saving	0.48	154	41.3	no	15.68

— Measurements of electrical quantities of ATV320 driven pump drive

Of all the four control modes of the ATV320 frequency converter in case of high flow and very low pressure, the pump motor consumed the least electric energy in U/F Energy Saving control mode.

As seen from Tab. 4, the pump motor current was lowest in U/F Energy Saving (0.9 A) and in U/F Quadratic control mode (1 A). The U/F Standard and SVC control modes had the same currents but higher than the other two control modes (1.1 A). During operation in U/F Standard and in SVC control modes, a overshoot occurred at the start up.

Table. 4. Results of measurements of electrical quantities of ATV320 driven pump drive

Control mode	Current [A]	Voltage [V]	Freq. [Hz]	Current overshoot	El. energy [Wh]
U/F Standard	1.1	172	41.2	yes	40.44
U/F Quadratic	1	150	41.7	no	31.47
U/F Energy Saving	0.9	93	43.7	no	17.67
Sensorless Vector Control	1.1	171	41.2	no	40.26

From Tab. 4 shows that the pump motor voltage was lowest in U/F Energy Saving control mode (93 V), then in U/F Quadratic (150 V), and highest in U/F Standard and SVC control mode (172 and 171 V). The values of the electric energy consumption of the pump motor are the highest for U/F Standard (40.44 Wh) and SVC control modes (40.26 Wh), followed by U/F Quadratic (31.47 Wh), and the lowest for U/F Energy Saving (17.67 Wh).

5. CASE OF HIGH PRESSURE AND HIGH FLOW IN THE SYSTEM

In the case of high pressure and high flow, the pressure reference value in the system is set to 3 bar, and the flow in the system is set to 11 L/min using a valve. Based on the measured pressure and flow, the hydraulic power of the pump in the system was calculated and it is 55.2 W. The values of pressure, flow and hydraulic power of the pump are the same for all 7 consumption measurements.

— Measurements of electrical quantities of ATV630 driven pump drive

Of all three modes of control of the Altivar ATV630 frequency converter in a case of high pressure and high flow in the system, the pump motor consumed the least electric energy in U/F Quadratic control mode.

From Tab. 5, it can be seen that the electric current of the pump motor was the lowest in the U/F Standard control mode (0.95 A) and the highest in the U/F Quadratic control mode (0.97 A). No overshoots occurred during the start up. The pump motor voltage was lowest in U/F Quadratic control mode (302 V), then in U/F Energy Saving (310 V), and highest in U/F Standard control mode (320 V). In none of the three control modes did an overshoot occur during a startup. Pump motor electric energy consumption values are highest for U/F Standard control mode (66.35 Wh), followed by U/F Energy Saving (65 Wh) and lowest for U/F Quadratic (63.37 Wh).

Table. 5. Results of measurements of electrical quantities of ATV630 driven pump drive

Control mode	Current [A]	Voltage [V]	Freq. [Hz]	Current oveshoot	El. енergy [Wh]
U/F Standard	0.95	320	43.2	no	66.35
U/F Quadratic	0.97	299	44.4	no	63.37
U/F Energy Saving	0.96	310	43.4	no	65

— Measurements of electrical quantities of ATV320 driven pump drive

Of all the four modes of control of the ATV320 frequency converter in case of high flow and high pressure, the pump motor consumed the least electric energy in U/F Quadratic control mode. From Tab. 6 it can be seen that the electric current of the pump motor was the lowest in U/F Standard, in SVC and in U/F Quadratic, which had the same values of electric current (1.7 A). The electric current in U/F Energy Saving was the highest (2 A). Overshoots did not occur.

Table. 6. Results of measurements of electrical quantities of ATV320 driven pump drive

Control mode	Current [A]	Voltage [V]	Freq. [Hz]	Current overshoot	El. energy [Wh]
U/F Standard	1.7	189	44.3	no	70.14
U/F Quadratic	1.7	180	45.9	no	66.92
U/F Energy Saving	2	158	47.4	no	68.67
Sensorless Vector Control	1.7	192	44.9	no	71.19

Tab. 6 shows that the pump motor voltage was lowest in U/F Energy Saving control mode (158 V), then in U/F Quadratic (180 V), and highest in U/F Standard (189 V) and SVC control mode (192 V). In no case does an overshoot occur. Pump motor electric energy consumption values are highest for U/F Standard (70.14 Wh) and SVC control modes (71 Wh), followed by U/F Energy Saving (68.67 Wh) and lowest for U/F Quadratic (66.92 Wh).

6. ELECTRICAL ENERGY SAVING ANALYSIS

After the measurements for all three cases were completed, the results of electricity consumptions for both frequency converters were obtained, which were presented in the previous chapter.

Based on the measurements it can be concluded that the pumps motors, in case of low flow and very low pressure and in case of high flow and very low pressure in the system, were the lowest consumers while they were controlled by frequency converters in U/F Energy Saving mode. According to the manufacturer's catalog, the U/F Energy Saving control mode is used as an energy saving mode with U/f^2 ratio control. A mode that reduces motor current in cases when motor load is reduced and preserves drive performance up to full load.

In the case of low flow and very low pressure and in the case of high flow and very low pressure in the system, the load was reduced to a minimum and the efficiency of the U/F Energy Saving mode came to the fore. Diagrams of electric currents and supply voltages of the control modes of both frequency converters in the case of low flow and very low pressure are shown on Fig. 9 and Fig. 10.

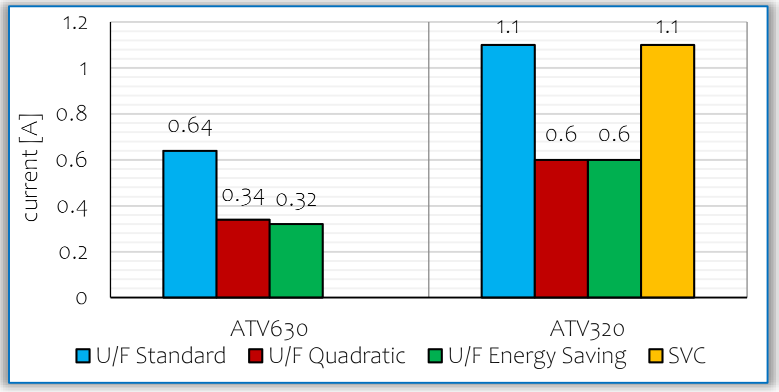

Figure 9. Currents of both motors in a case of low flow and very low pressure in the system

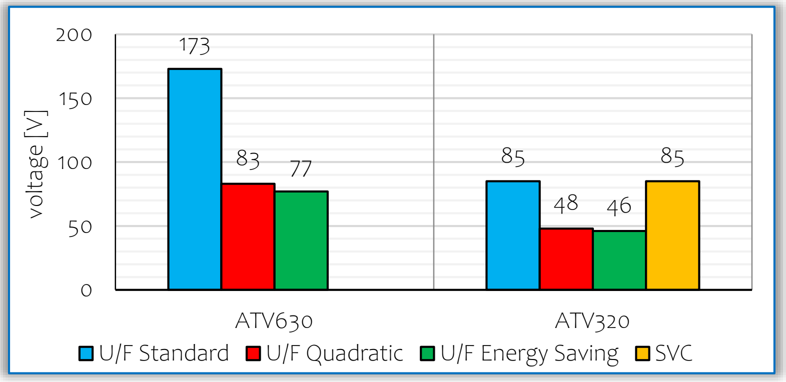

Figure 10. Voltages of both motors in a case of low flow and very low pressure in the system

In case of low flow and very low pressure in U/F Standard control mode of ATV630 frequency converter and in U/F Standard and SVC control mode of ATV320 frequency converter a current overshoot occurred during the stat up, while in other modes of both converters that was not the case. The voltage overshoot during the startup of the engine was not present in any mode. The comparison of the consumed electric energies of the control modes of both frequency converters in the case of low flow and very low pressure are shown on Fig. 11.

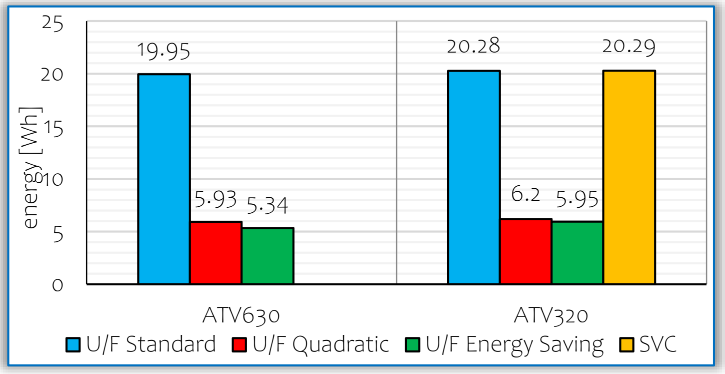

Figure 11. Electric energy consumption of the control modes of both regulators in case of low flow and very low pressure in the system

As can be seen on the diagram, on Fig. 11, the second most efficient control mode of both frequency converters is U/F Quadratic, which is almost similar to U/F Energy Saving control mode, while U/F Standard and Sensorless Vector Control are the most inefficient modes. The diagram shows that the control modes of the ATV630 frequency controller are lower electric energy consumers than the same modes of the ATV320 frequency converter.

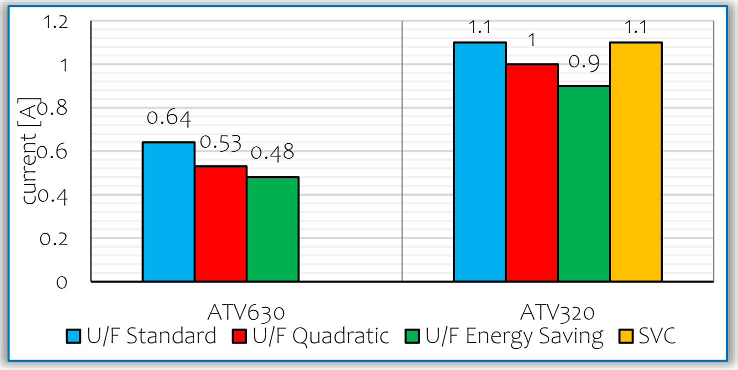

Figure 12. Currents of both motors in a case of high flow and very low pressure in the system

Diagrams of electric currents and supply voltages of the control modes of both frequency converters in the case of high flow and very low pressure in the system are shown on Fig. 12 and Fig. 13.

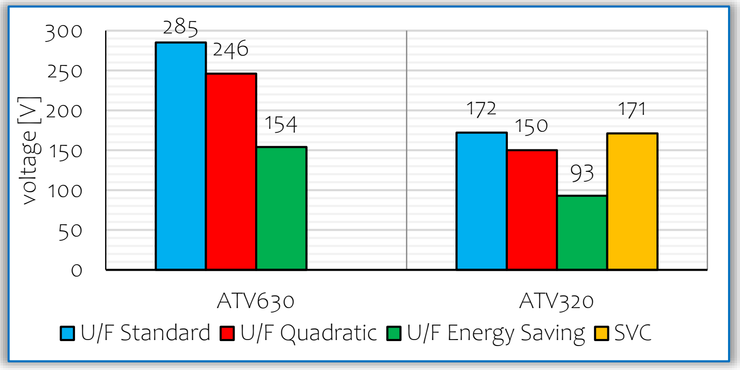

Figure 13. Voltages of both motors in a case of high flow and very low pressure in the system

In the case of high flow and very low pressure in the system in U/F Standard control mode, there was an overshoot of current during the startup of the motor for both frequency converters. In other modes, steady state was reached without an overshoot. There was no voltage overshoot.

The comparison of the consumed electric energies of the control modes of both frequency converters in the case of high flow and very low pressure are shown on Fig. 14.

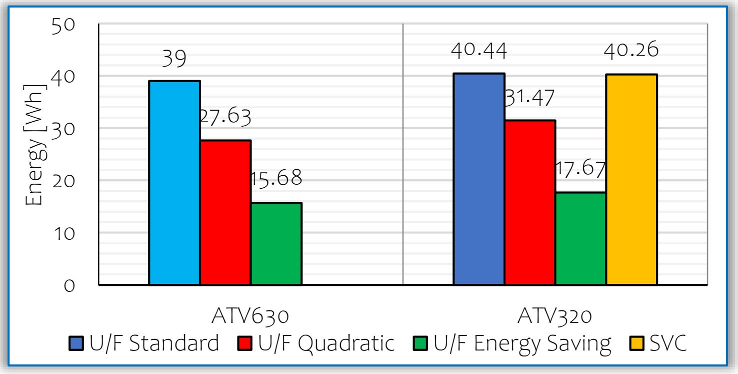

Figure 14. Electric energy consumption of the control modes of both regulators in case of high flow and very low pressure in the system

On the diagram, on Fig. 14, the most efficient is the U/F Energy Saving control mode, followed by the U/F Quadratic, while the U/F Standard and SVC are the most inefficient control modes. The diagram shows, in this case as well, that the control modes of the ATV630 frequency converter are lower electric consumers than the same ATV320 modes.

The low electric consumption of the U/F Energy Saving control mode has come to the fore in the previous two cases of system setup, due to the low load. But when the load in the system is much higher, when the operating conditions of the system are close to the nominal, then the U/F Quadratic control mode comes to the fore.

In the U/F Quadratic control mode, the voltage-frequency ratio is not linear, as in standard mode (U/f), but U/f^2 ratio. Control mode intended for variable torque applications and commonly used for pumps and fans. Diagrams of electric currents and supply voltages of all control modes of both converters in case of high pressure and high flow in the system are shown on Fig. 15 and Fig. 16.

In the case of high pressure and high flow in the system in any of the control modes there was no overshoot of current or voltage when starting the engine.

The comparison of the consumed electric energies of the control modes of both frequency converters in the case of high pressure and high flow in the system are on Fig. 17. As can be seen on the diagram, on Fig. 17, the lowest consumer is U/F Quadratic control mode, followed by U/F Energy Saving, while U/F Standard and SVC are the largest consumers of electricity. The diagram shows, in this case as well, that the control modes of the ATV630 frequency converter are more efficient than the same modes of the ATV320 frequency converter.

For cases of system operation without heavy loads, the most efficient control mode is U/F Energy Saving. As the load in the system increases, the efficiency of the U/F Energy Saving control mode decreases, and in these cases the U/F Quadratic control mode should be used for lower electric consumption. For cases where the load is not known the optimal control mode is U/F Quadratic. Mode that can provide efficiency because it uses U/f^2 ratio, as well as U/F Energy Saving, but also a mode that can answer to the requirements of variable torque, as according to the manufacturer's catalog.

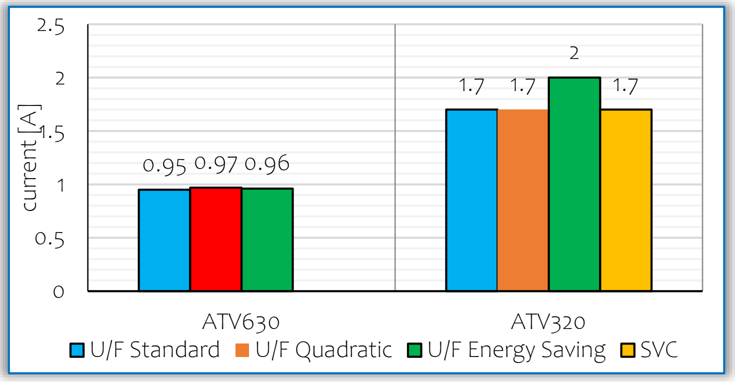

Figure 15. Currents of both motors in case of high pressure and high flow in the system

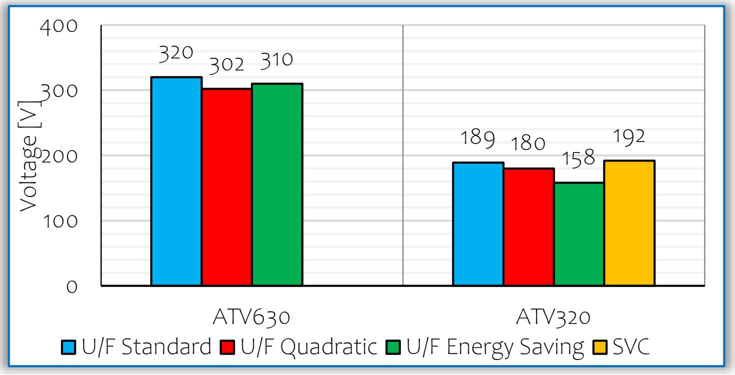

Figure 16. Voltages of both motors in case of high pressure and high flow in the system

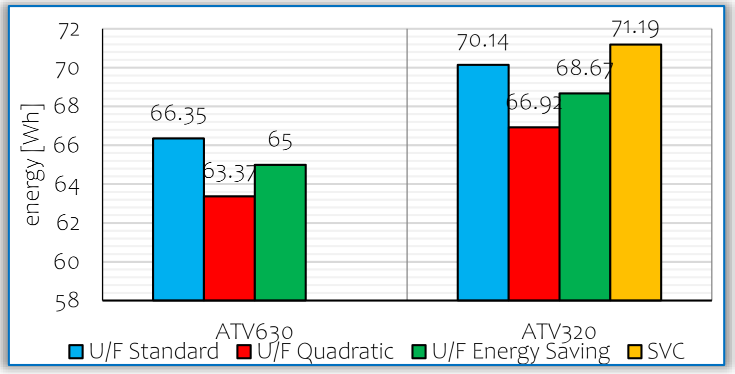

Figure 17. Electric energy consumption of the control modes of both regulators in case of high pressure and high flow in the system

8. CONCLUSION

The research conducted in this paper aimed to investigate whether different modes of controlling the drive can affect and how much the increase of the energy efficiency of the overall system.

Measurements of Pedrollo PK65 pump motor consumption were performed for all control modes of both frequency converters. Measurements were performed in three cases of system setup and in each of the three cases the most efficient control mode of each frequency controller was determined and the control modes efficiency were compared between the two used converters.

In the case of low flow and very low pressure and in the case of high flow and very low pressure in the system, the load was reduced to a minimum and the most efficient control mode of both frequency converters was U/F Energy Saving. The second most efficient mode of both frequency converters was U/F Quadratic, and U/F Standard and SVC modes were less efficient modes. In a case of high pressure and high flow, the most efficient control mode of both frequency converters was U/F Quadratic, then U/F Energy Saving, while U/F Standard and SVC modes were the highest consumers of electricity.

In each of the three system setup cases, the control modes of the ATV630 frequency converter were lower electric consumers than the same ATV320 frequency converter modes. The reason is partly that the ATV630 is three phase, so the currents for the same powers are lower. With the ATV320, the currents are higher, so the losses in the converter are higher. In addition to the above, the ATV630 is adapted for use in the process industry, for driving pumps and fans that have exponential load characteristics, while the ATV320 is intended for the machine segment where constant loads with higher starting moments are generally expected.

Conclusion is that the U/F Energy Saving control mode is the most efficient for the operation of the system in the case of no heavy loads. As the load in the system increases, the efficiency of the U/F Energy Saving control mode decreases and the efficiency of the U/F Quadratic control mode increases. However, the load in the system will often not be known and then the U/F Quadratic control mode should be used, which would be the optimal mode. A mode that can meet the requirements with variable torque but also can provide energy efficiency because it uses the U/f^2 ratio, as well as U/F Energy Saving. This shows that the choice of control mode, in certain operating conditions, is very important from the aspect of energy efficiency.

Note: This paper was presented at International Conference on Applied Sciences – ICAS2022, organized by University Politehnica Timisoara, Faculty of Engineering Hunedoara (ROMANIA) and University of Banja Luka, Faculty of Mechanical Engineering Banja Luka (BOSNIA & HERZEGOVINA), in May 25–28, 2022, in Banja Luka (BOSNIA & HERZEGOVINA)

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ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665