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Technical and economic analysis of Soft Starter Providing in LV Electrical Installation

The main aim of this paper is to identify the consequences magnitude of providing electronic starters, also called Soft Starters, in AC electrical motors with largest powers and the economical appreciation of this measure. Through this, it aims not only to identify the technical and economic arguments for applying more decided the provision of electronic starters, but also the limits of its application, given the great diversity of receivers rated power. Thus, it is appreciated that there is no question of applying Soft Starters for the whole power range of asynchronous motors. In context of the proposed analysis, a summary of electronic starters issues is made which may be a guide of their choice and application, facilitating the specialists access in the technical manuals of the companies producing Soft Starters.

Keywords: Soft Starter, LV distribution network

1. Introduction

The short-circuit protections and conductors sizes from both circuits and columns are strongly related to the starting, respectively peak current size [1]. From this it can be concluded that any method that would significant reduces starting currents in special for largest receivers could bring economies through the following aspects:

- decreasing of rated currents of the short-circuit protection equipment from the circuits and columns;
- reducing the conductors sizes from the receivers circuits with the largest powers and from the distribution panels supplying columns;
- simplifying the protection selectivity issue at the transformer cells;
- increasing the operating time of driven mechanical transmissions.

The idea of making equipment for controlling the starting regimes of alternating current (AC) electrical motors has been developed together with the application of power converters in adjustable drives. Known as electronic starters or Soft Starters (SSt), this equipment is produced in a large range of types and sizes, with different operating run, adjustable to the desired setting type and at accessible costs.

2. Soft Starters

2.1. AM starting

Direct starting of squirrel cage asynchronous motors (AM) leads to appearance of a starting current in the electrical circuit given by:

$$I_p = \lambda \cdot I_n \text{, A,} \qquad (1)$$

where λ is the relative starting current [1], with values in $\lambda \in \{3{,}5 \div 9\}$;

I_n – AM rated current calculated with:

$$I_n = \frac{P_n}{\sqrt{3} U_{\ln} \eta_n \cos\varphi_n} \text{, A,} \qquad (2)$$

given that P_n has the significance of useful power, in the case of AM.

Most of the electric power suppliers limits the power of the AM which can be started through direct coupling at P_n= 5,5 kW [2÷4]. Regarding to AM fed through power substations, the rated power of those that can be directly started is limited at 20% of the substation transformers rated power.

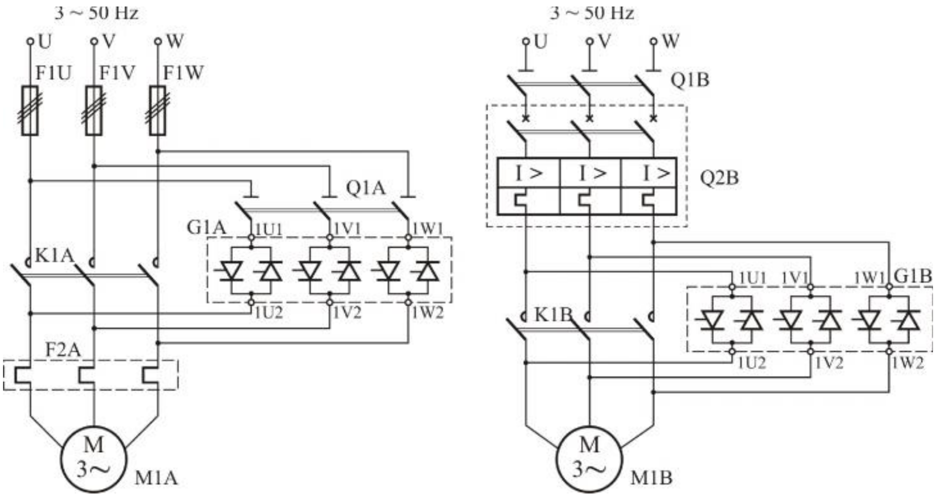
Between the known starting methods for AM, the star-delta starting is applicable only to those machines that are built for delta running connection; the star-delta starting scheme leads to reduce the starting current by three times.

Regarding starting with autotransformer, applied to hundreds of kW motors, it is relatively hard and the equipment is gauge and less reliably. Even if the stating current intensity can be limited, for every auto-transformer plot switching it appear current and torque peaks.

Starting with resistances in the rotor circuit, applicable to wound rotor AM, has the advantage of ensuring a determined interval of current variation in startup mode, but both power resistors and contactors for their switching are real sources of inconvenience in operation.

2.2. Starting with SSt

The SSt represents in fact an AC variator, running on constant frequency, equal with the supplying network one. The SSt power circuit includes on each phase a pair of thyristors in anti-parallel, as shown in Fig. 1. Some producers provide the group of thyristors in anti-parallel only on two phases of the receiver circuit. Connecting the electronic starter, identified by the reference G1A is done in parallel with the main contactor K1A (Fig. 1.a), normally present in the AM power circuit, having the protection provided by the pair of apparatus fuse (F1U, F1V, F1W) - thermal relay (F2A). By providing additionally the switch Q1A, the work safety requirements are fulfilled on both sides of the receiver circuit (Fig. 1, a).



a b

Figure 1. Connection schemes of SSt in AM power circuits: a – circuit equipped with fuses, contactor and thermal relay; b – circuit equipped with automatic circuit breaker.

In exchange, when the AM power circuit protection is provided by circuit breaker (Q2B, Fig. 1, b), the SSt (G1B) coupling in circuit requires the additional contactor K1B providing, meant to short-circuit the SSt power section when its function has ceased [5, 6].

2.3. SSt structure and working

The SSt block scheme is presented in Figure 2 where a block level representation was used for the power circuit G1, given that its power component was already presented (Fig. 1).

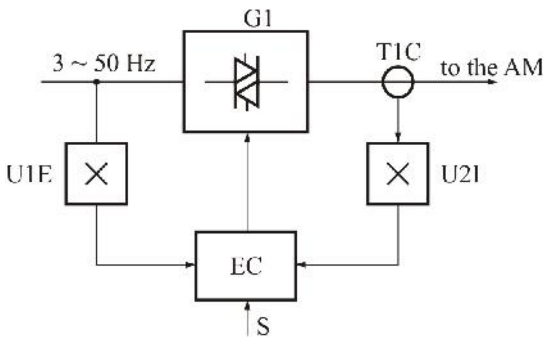


Figure 2. SSt block scheme.

The EC command block, with analogical, digital or combined operation, receives signals from the voltage (U1E) and current (U2I) transducers and according to the options expressed by the S command it provides firing signals of thyristors from the power circuit G1 in order to achieve the established starting regime.

Sometimes, in the SSt composition is included an electronic overload relay (EOL), which ensures a more effective protection of the motor against overload currents than the bimetallic relay, because the admitted overload is evaluated by computing according to the real variables from the circuit [6].

By setting the voltage initial value, the desire value for the starting torque may be ensured, providing the acceleration framing in an established range. An initial voltage of (30÷40) % and starting times of (5÷10) s are considered suitable for most applications [6].

The operating regimes which can be ensured through the SSt command block are generally the following: limiting the current in AM windings; limiting the mechanical torque to the motor shaft; startup regime imposed time; shutdown imposed duration; frequency modulation of the output voltage.

The last of these functional achievable regimes is limited in applications due to the low "quality" of the current and torque [5].

The dependence between the control angle α and the voltage r.m.s. value applied through SSt, at the AM terminals, is given by the relationship:

$$U_{eM} = U_M \sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin(2\alpha)}{2\pi}} \text{ , V;} \quad (3)$$

both the α angle significance and the dependence rendered by (3) are shown in Figure 3, where the voltage is given more generally, in percent:

$$U_{eM\%} = (100 \cdot U_{eM})/U_M \text{ , \% .} \quad (4)$$

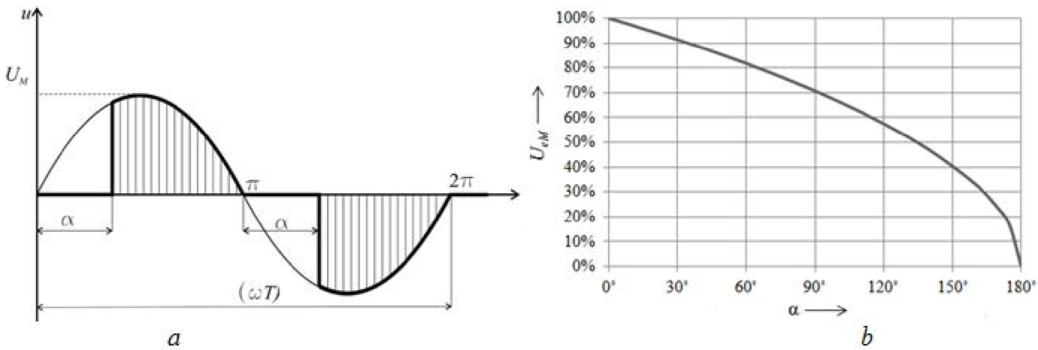


Figure 3. Voltage given by SSt, in relation with the α command angle:
a – voltage shape; b – voltage variation, in percent.

The control of the α angle, given by the command block EC (Fig. 2) is set so that the startup current to be constant maintained, with λ_D multiplication order, established by the installation designer in the range $a_D \in [a_{D\min}, a_{DMax}]$.

3. Consequences of SSt set up

3.1. Receiver circuits case

The technical consequences analysis, at providing SSt on receiver circuits, was made for an squirrel cage AM receivers range, from the normalized values series [1]. The dimensioning calculus for the circuit elements, as equipment and electrical conductors, are in accordance with the method detailed in [2] and is developed in accordance with the standard [4] provisions. The calculus proved that the SSt mounting on AM circuits with the relative operation duration DA_n=1 does not entail the diminishing of rated or adjusted currents of the protection equipment and neither the reduction of the conductor section. Therefore, cost savings are not recorded with the protection devices and electrical conductors.

If yet the overload protection with thermal relay would be replaced by protection with thermo-sensitive elements, implanted in receivers to be protected, the selectivity condition of the fuse with the thermal relay will not be necessary anymore, thus significant reductions of the rated currents of fuses and fuses cap will result, according to Table 1 (DA_n=1).

Table 1. Comparative data for receiver circuits sizing, with direct (Dir.) or SSt starting, in the case of thermo-sensitive protection and DA_n=1

Crt. No.	Size	Motor Rated Power, kW									
		15		18,5		22		30		37	
		Dir.	SSt	Dir.	SSt	Dir.	SSt	Dir.	SSt	Dir.	SSt
1	Unbreaking condition at starting current, of fuse, I_{Fn}, A	≥81	≥23,2	≥98,8	≥28,2	≥118	≥33,6	≥157	≥45	≥193	≥55
2	Fuse rated current, I_{Fn}, A	100	**25**	100	**35**	125	**35**	160	**50**	200	**63**
3	Fuse cap rated current, I_{FSn}, A	100	**25**	100	**63**	200	**63**	200	**63**	200	**63**
3	Electrical conductor, section type, mm^2	FY6		FY6		FY10		FY16		FY25	

It comes out that using protection devices with thermo-sensitive element, which may be called temperature protection, fuses result significantly lower, both in terms of the cap rated current and of the fuse rated current. Thus, if the direct startup case and the overload protection are compared with the starting using SSt one and the temperature protection (Table 1, right column, for every P_n), a 2-3 steps reduction of the cap rated current and with 5-6 steps of the fuse rated current may be emphasized, which become significant for costs also.

Regarding the electrical conductors, their sections are also reduced with one step, but only at the rated power range $P_n \in \{18,5;22;30\} kW$.

The receiver circuits sizing cases for two rated powers of squirrel cage AM, presented in distribution schemes of some tools-machines are examined in Table2. The relative operation time was considered DA_n=0,4, acceptable for a wide range of applications.

Table 2. Receiver circuit sizing with and without SSt for a subunitary operating time, DA_n=0,4

Crt. No.	Size	Motor Rated Power, kW					
		11		15		22	
		Dir.	SSt	Dir.	SSt	Dir.	SSt
1	Rated current, I_n, A	21,8		28,9		42	
2	Demand current, I_c, A	11		18,3		26,6	
3	Starting current, I_p, A	141,4	**43,5**	202,6	**57,9**	294	**84**
4	Thermal relay seting current, I_{rt}, A	11,5		18,5		27,2	
5	Unbreaking condition at starting current, of fuse, I_{Fn}, A	≥56,5	≥17,4	≥81	≥23,2	≥117,6	≥33,6
6	Selectivity condition of fuse with thermal relay, I_{Fn}, A	≥34,5		≥55,5		≥81,6	
7	Chosen fuse, I_{FSn}/I_{Fn}, A	63/63	63/**35**	100/100	**63/63**	200/125	**100/100**
8	Electrical conductor, section type, mm²	FY6	**FY1,5**	FY6	**FY4**	FY10	**FY6**

Indeed, for every three analyzed AM receivers, decreases with 1-2 steps comes out at the fuse rated current level, accompanied sometimes with a one step decrease for the cap rated current. Also, the conductor section is reduced with one step, for receivers with 15 and 22 kW as rated powers, and the reduction will be with 3 steps for conductors in the 11 kW receiver case.

In conclusion, we can say that the effect of providing SSt is being felt in equipping the receiver circuits, the more the rated operating durations of these ones are smaller.

3.2. Consequences at Distribution Panel Level

Further on, the AM with P_n=22 kW and DA_n=0,4 (Table 3) is considered, which represents the main driving motor in the semi-automatic lathe ST2 [2]. The consequences of using SSt for AM with P_n=22 kW are examined, by comparison, in Table 3, at the machine-tool level. To be noted that SSt are not considered to be used for the other motors.

The maximum inrush current I_{pM}, which is the starting current of the 22 kW AM (3rd line), has much different values in the two cases, so that the peak current I_v from the machine-tool circuit (5th line) decreases to less than one third, in case of using SSt. In consequence, the fuses selection conditions are expressed also through different values (2nd and 3rd lines, from fuse).

Table 3. Comparative data for machine-tool circuits (ST2 lathe), for cases where SSt was not used, respectively it was used to the main motor

Element	**Size or Solicitation**	**Relationship or Symbol**	**Facility**	
			ST2	ST2 with SSt
Sub-consumer	Demanded current	I_c, A	34,8	
	Maximum startup current	I_{pM}, A	294	**84**
	Demanded current of the other (n-1) receivers	$I_{c(n-1)}$, A	8,24	
	Peak current	$I_v = I_{pM} + I_{c(n-1)}$, A	302	**92,2**
Fuse	Long term thermal solicitation	$I_{Fn} \geq I_c$	≥34,8	
	Unbreaking peak current	$I_{Fn} \geq I_{pM} / c + I_{c(n-1)}$	≥125,8	**≥41,8**
	Selectivity with downstream fuse	$I_{Fn} \geq 1{,}5625 \cdot I_{FnpIM}$	≥195	**≥156**
	Chosen fuse	LFi; ($I_{n\,soclu}/I_{n\,fuzibil}$)	200/200	200/**160**
Electrical conductor	Permanent regime thermal stability	$I_{Cadm} \geq I_c / (aK)$	≥33,1	
	Thermal stability at I_{sc}	$I_{Cadm} \geq I_{Fn} / 3$	≥66,7	**≥53,3**
	Thermal stability at I_v	$s_C \geq I_v / J_{adm}$	8,6	**2,6**
	Chosen conductor	Tip FY... mm^2	FY25	**FY16**

Finally, a reduction with one step of the fuse rated current may be noticed (from 200 A to 160 A) as well as for the conductors sections on this machine-tool feeding circuit.

The consequences of using SSt at 22 kW AM from the considered machine-tool is next examined at the feeding column level of the distribution panel (DP) and of the LV general panel (GP). A mechanical processing unit is considered as general end-user, having a total installed power of 372 kW, with a relatively heterogeneous structure. From all 44 machine-tools and receivers, 11 are of ST2 lathe type, as previously mentioned. It was determined as optimal, two distribution point in LV, so two DP are foreseen.

The comparative data from Table 4 allow a concrete vision about consequences of using SSt on the higher power AM (here 22 kW). Firstly, a 2 steps decrease of the rated current may be observed for the fuse from the feeding column of DP1 and 1 step decrease of the form cap rated current. However, it must be noticed how close are in terms of values all three conditions which determine the choice of fuse from the DP1 column.

Regarding the electric conductor from the DP1 column, owing the fact that the thermal stability, in the steady state, represents the most restrictive condition,

$$I_{Cadm} \geq \frac{I_c}{aK} = 224\ A\,, \tag{5}$$

the column conductor section results of the same value in both cases.

Passing to the GP, it may be observed that, from the three imposed conditions for choosing the fuse, the one referring to selectivity with the maximum downstream fuse, is the determining one. Consequently, the result is again more favorable for using SSt at the AM with the highest powers (Table 4, last 2 columns). Even if the fuse cap has the same value, in both analyzed cases, the fuse rated current results with 2 steps lower, which has significant consequences for ensuring the selectivity at the substation level [7].

Table 4. Comparative data for DP1 and GP, for cases in which SSt was not used, respectively was used for the highest power AM

Element	Size or solicitation	Relationship and Symbol	Distribution Panel			
			DP1	DP1 with SSt	GP	GP with SSt
Sub-consumer	Transient component of the peak current	$I_{vt} = I_{pM}$, A	294	**84**	294	**84**
	Demanded current of the other (n-1) receivers	$I_{c(n-1)}$	221		336	
	Peak current	$I_v = I_{vt} + I_{c(n-1)}$, A	515	**305**	630	**420**
Fuse	Long term thermal solicitation	$I_{Fn} \geq I_c$, A	≥235		≥341	
	Unbreaking peak current	$I_{Fn} \geq I_{pM}/c + I_{c(n-1)}$, A	≥329	**≥245**	≥454	**≥370**
	Selectivity with downstream fuse	$I_{Fn} \geq 1,5625 \cdot I_{Fn\,pM}$, A	≥313	**≥250**	≥625	**≥391**
	Chosen fuse	Tip $I_{n\,soclu}/I_{Fn}$	630/400	**315/250**	630/630	630/**400**
Electrical conductor	Permanent regime thermal stability	$I_{Cadm} \geq I_c / aK$, A	≥224		≥324	
	Thermal stability at I_{sc}	$I_{Cadm} \geq I_{Fn}/3$, A	≥133	≥83,3	≥210	≥133
	Thermal stability at I_v	$s_C \geq I_v / J_{adm}$, mm²	≥14,7	≥8,7	≥18	≥12
	Chosen conductor	FY ... mm²	FY120 (în tub)		FY120 (libere în aer)	

Similarly as in the case of DP1 feeding column, the condition about thermal stability, in the steady state is determining and, being the same in both cases, leads to choosing the same conductor section, for the LV general column. Speaking about connections in LV, in the transformer cell, in air, same type conductors were chosen, resulting also the same section.

3.3. Economic aspects

Regarding the costs which differentiate the solution of using SSt, but only for AM with highest powers, Table 5 was conceived in order to include those elements of the installation which result different in the SSt absence and in the SSt presence. It can be emphasized that it appears additional costs for the solution with SSt for the considered data. These differences depend on the equipment providers and also on the number of receivers with highest powers.

Table 5. Costs that differentiate the SSt use solution for AM with highest powers

Crt. no.	Element	Unit cost m. u.	No. of pieces/ m	Partial costs	
				Installation, without SSt	With SSt at 22 kW AM
1	Receiver circuit fuse, 200/125	32,2	11	354,2	-
2	Receiver circuit fuse, 100/100	23,8	11	-	261,8
3	SSt (type DS7-EATON)	1.680	11	-	18.480
4	Equipment cicuit fuse, LFi 200/200	49,1	11	540	-
5	Equipment cicuit fuse, LFi 200/160	35,2	11	-	387,2
6	Equipment circuit wire, FY25	12,61	1.540	19.420	-
7	Equipment circuit wire, FY 16	6,81	1.540	-	10.488
8	DP1 fuse, MPR 630/400	86,1	1	86,1	-
9	DP1 fuse, MPR 315/250	65,9	1	-	65,9
10	GP fuse, MPR 630/630	98,4	1	98,4	-
11	GP fuse, MPR 630/400	86,1	1	-	86,1
			TOTAL, m.u.	**20.498,7**	**29.769**

For example if the maximum mounted SSt are 5, the differentiation costs were less already for the SSt solution.

In addition, the active losses costs might be added, much diminished in the case of a soft starting with SSt as well as the costs related to the mechanical parts maintenance, which can be much higher in the direct starting case, without SSt.

4. Conclusions

Providing SSt on the AC circuits of the electrical motors represents a particularly useful solution, both for the good operating and increased reliability of the driven machine tool, as well as for the LV distribution installation.

In the case of overload protected receivers with thermal relays, it was found that installing SSt leads to a diminution of the fuses rated currents and of the conductors section only if the receivers are working in intermittent run. As the operating duration is less, the differences between variants of the direct starting, respectively with SSt are accentuated.

Reducing the starting currents by using SSt has positive effects, further on, at the machine tool level, as well as the DP and GP ones, through significant reductions of the nominal currents of the protective devices, as well as by reducing the section of conductors.

At the LV general column level is however possible to no longer register decreases of the section conductors, because thermal stress condition, in the steady state, expressed in relation to the demanded current, becomes decisive.

The problem of decreasing the protective devices rated on the supplying path of the AC electric motors, controlled by SSt, bring back in actuality the solution of replacing the overload protection through thermal relays with over-temperature protection, carried out with relays and temperature transducers, especially for receivers with the largest powers.

It may be noted that the economic tests have to be made for each concrete case, in part, by considering the different offers of companies producing SSt, protection devices and electrical conductors.

Indifferently of the economic evaluation results, the SSt positive effect is outlined regarding the important diminution of the mechanical and electrical stresses during starting and regarding the selectivity at the transformer cell level from a power substation, as well as over a significant reducing of the short-circuit currents, by the fuses limiting effect.

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