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RECENT AC VARIABLE SPEED MOTORS

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I. INTRODUCTION

The progress and development of semiconductor, converter and electronic control technologies in recent years has led to a gradual expansion in the fields in which power converters using semiconductors are applied. However, inverter technology which has developed with high speed thyristor manufacturing techniques has resulted in a great expension of the possibilities of variable speed drive of AC motors. As a result, a large number of AC variable speed motors have been developed and part of them have reached the practical stage. This article will introduce the Fuji Electric AC variable speed motors which are being supplied for practical use.

II. VARIABLE SPEED DRIVE OF AC MOTORS

Motors can be classified as AC motors (induction and synchronous motors) and DC motors. AC motors are used mainly as a constant speed motors, but for variable speed drive applications, variable frequency control by Motor-Generator type frequency converters, secondary resistance control in induction motors, secondary slip power control, primary voltage control, eddy current control, etc. are used. DC motors are employed mainly for variable speed drive and a typical drive is the static Leonard system. Since there are big differences between the Leonard drive of DC motors and the variable speed drive of AC motors in respect to speed control range, possible operation quadrants, efficiency, and control performance, DC motors are used exclusively for application of variable speed and reversible operation requiring high efficiency and high performance. The main reason why DC motors are used typically as variable speed motors is that the speed can be regulated easily over a wide range by changing the DC voltage and exciting current by means of easy comparative control. Since the speeds of AC motors are determined essentially by the supply frequency, it is necessary to change the supply frequency for wide ranging highly efficient speed control. However, no suitable method has been found for this change except by providing an Motor-Generator type frequency converter which was used previously.

In the case of induction motors, the speed can be changed to a certain degree simply by regulating the motor torque without changing the supply frequency (i.e. without changing the synchronous speed) but in this case, it is widely known that the loss increases in proportion to the slip. The Scherbius system and the Cramer system are used to absorb this slip power again as electrical or mechanical energy.

Inverter techniques are utilized as a means to change the supply frequency and with the progress in inverter techniques variable speed drive techniques of AC motors using semiconductor converters (mainly thyristor converters) have developed remarkably.

When AC motors are used for variable speed drive with semiconductor converters, the following points have been achieved by elimination of brushes and commutators.

1) Conquest of manufacturing limits concerning speeds and capacities in DC motors

DC motors have brushes and commutators so that they are limited in respect to maximum speeds and capacities by possible commutation limits but in brushless and commutatorless motors, these limitations are removed and the motors can be manufactured with speeds and capacities which were formerly impossible.

2) Decreasing restrictions concerning motor environment

Because of the elimination of sparks and commutators, it is relatively easy to place the motors in environments which were formerly bad for DC motors such as corrosive or inflammable gases. It is also possible to avoid the scattering of particles caused by brush wear near the motor.

3) Kabor savings and maintenance-free

The necessity of saving maintenance labor has increased gradually because of labor shortages and particularly in places where high speed DC motors or many DC motors are used, the burden required for maintenance of brushes and commutators can not be overlooked. When the maintenance and inspection is difficult because of the location of the motors, for example when in special undersea applications, it is necessary to make the motors maintenance free by removing the motor brushes and commutators.

Under such circumstance, the application of AC motors for variable speed drive has progressed and as a result, many types of AC variable speed motors have been developed. Part of these are in practical use. However, these new AC variable speed motors can not always replaced the present variable motors such as the Leonard control DC motors. The main reason for this is because they have not yet always achieved the same control and economy characteristics as the existing variable speed motors such as the Leonard control DC motor in the various AC variable speed motor described previously. It is essential to sufficiently understand these two aspects of present day AC variable speed motors so that applications will be effective and appropriate.

At present, AC variable speed motors have passed from the development stage to the practical stage internationally. To complete them, it is necessary to return to the torque generation principles of AC motors and look into them from the standpoint of control theory. In the Leonard drive of DC motors, it is sufficient to handle the DC voltage and current as scalar values but for AC motors, the voltage, current and magnetic flux must be handled as vector values. Through the design of motors and converters on the basis of this control theory, improvements in performance and cost reductions of the AC variable speed motors will be possible in the future.

III. TYPES AND CHARACTERISTICS OF AC VARIABLE SPEED MOTORS

There are different methods of classfying AC variable speed motors depending on the standpoint but they can roughly be classified as in *Table 1* as commutatorless motors, variable frequency control motors and secondary slip power control motors. The basic features of these will be described mainly in comparison with Leonard drive DC motors.

1. Commutatorless Motors

These are motors with no commutators which act directly on the principle of torque generation of DC motors. The commutators of the DC motors are replaced by thyristor rectifiers (transistors in small capacity motors). The current flows in the required armature windings by means of selective conducting of the thyristors in accordance with the field poles' (rotors') position and the torque is generated. The motor used is a synchronous motor. Therefore, in principle, speed control is possible in the same way as voltage and field control, etc. in DC motors. These operating characteristics are very similar to the Leonard drive of the DC motors.

However, the operating principles are different from those of DC motors, and so care must be taken concerning the differences in characteristics which arise. The first is that in the commutatorless motors, the use of thyristors equivalent only to the commutator of the DC motor is impossible in practice from the standpoint of thyristor utilization factors and it seem to the fact that there are very few commutators in DC motors. Therefore, torque pulsations arise in accordance with the rotor position.

These torque pulsations present almost no problems in many case during high speed operation but during low speed operation low frequency torque pulsations appear and since it is possible for the instantaneous starting torque to be below the average starting torque because of the rotor position during starting, some type of countermeasure is necessary depending on the application. The second is the fact that the operation equivalent to mechanical commutation in the DC motors is performed by firing and putting out of thyristor. This means that the problem of commutation in the DC motors is replaced by the thyristor commutation problem. The specifications related to the thyristor commutation phenomenon or the current direction changeover of the thyristor converter play a role in overload withstand, the torque direction reversing time, etc. in commutatorless motors. There are various types of thyristor connection and commutation systems, each of which have their own features.

1) DC type machine commutating commutatorless motor (MC Permotron)

This type features a conventer with DC link and a forced commutated system. This connection system is the best for high capacity motors because of the high thyristor utilization factor. Because the thyristor converter part near the motor terminals has a commutation system using counter electromotive force of the moter. Therefore a simple means of supplementing commutation is necessary in the low speed operation range.

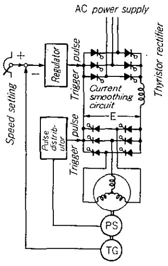
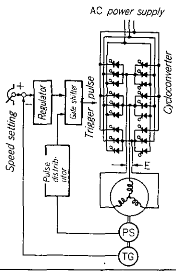
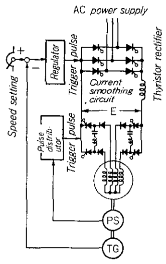
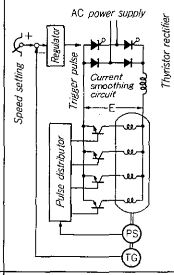
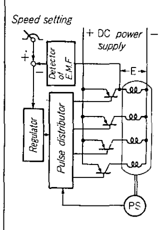
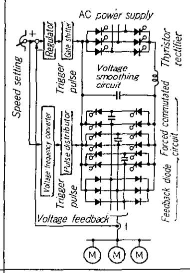
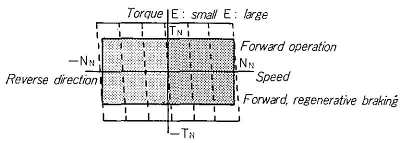
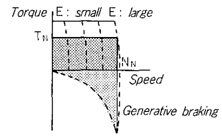
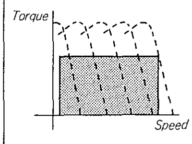
2) AC type commutatorless motor (AC Permotron)

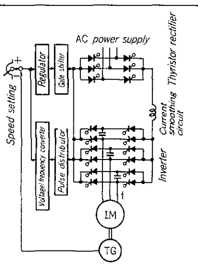
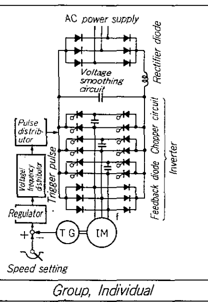
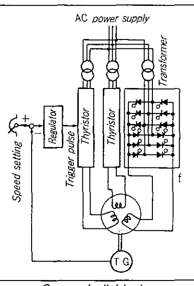
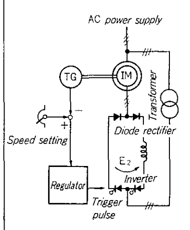
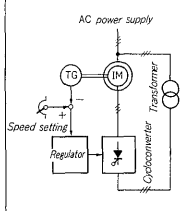
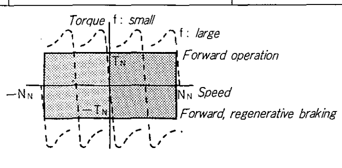
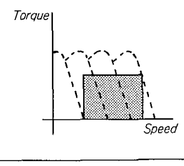
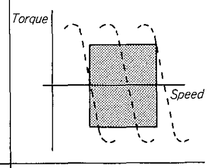
This type features the use of a cycloconverter. Since the thyristor utilization factor is lower than in the MC Permotron motors, it is suitable for medium capacity motors. Because the commutation due to power supply voltage is normally effective, no special auxiliary circuit for commutation is required in the low speed range.

3) Commutatorless motor with forced commutated inverter (DC Permotron)

This type is similar to that of the MC Permotron but a forced commutated circuit is used in the thyristor converter part near the motor terminals. Because of this forced commutated circuit, it is possible to make the angle of advance γ_0 small. The motor power factor is improved and the torque ripple is smaller.

Table 1 Comparison of AC variable speed motors

Type	Commutatorless motors					Variable frequency control motors
Brand names	MC *Permotron*	AC *Permotron*	DC *Permotron*	TR *Permotron*	Electronic motor	Voltage controlled type inverter with DC link FRENIC 1000
Type of motor	Claw-pole synchronous motor or wound rotating field synchronous motor	Claw-pole synchronous motor or wound rotating field synchronous motor	Synchronous motor with permanent magnet	Synchronous motor with permanent magnet	Synchronous motor with permanent magnet	Squirrel cage induction motor or synchronous motor
Construction						
Group or individual operation	Individual	Individual	Individual	Individual	Individual	Group
Output power range	30 to several thousand kW	3.7~200kW	2.2~30kW	0.2~1.5kW	0.4~90W	12.5~200kVA
Speed range	500~3000rpm	500~3000rpm	500~3000rpm	500~10000rpm	500~6000rpm (60000rpm)	500~9000rpm
Speed control range	1 : 20	1 : 20	1 : 20	1 : 20	1 : 20	1 : 20
Torque characteristics	Constant torque	Constant torque	Constant torque	Constant torque	Constant torque	Constant torque
Speed-torque characteristics (typical example)						
Features	● If torque pulsation is disregarded, control and torque characteristics are same as those of DC motors.					● Suitable for sectional, irreversible drive of many motors. ● High speed drive with no relation to mains power supply frequency. ● Motor terminal voltage is square wave and current sinusoidal.
Typical applications	● General industrial machinery such as textile machinery, steel rolling machinery, extrusion machinery, calenders, fans, pumps, centrifuges and deep sea diving equipment. ● In the long term, can cover fields in which DC motors are now applied.			High speed bobbins	Computer peripheral equipment, measuring instruments, office machines, high speed bobbins, sounding equipment, VTR	Textile machinery, roller tables, conveyer lines and machine tools

Type	Variable frequency control motors			Secondary slip power control motors	
Brand names	Current controlled type inverter with DC link FRENIC 2000	Pulse width modulation type inverter	Cycloconverter	Static Scherbius	Supersynchronous Scherbius
Type of motor	Squirrel cage induction motor	Squirrel cage induction motor	Squirrel cage induction motor and synchronous motor	Wound-rotor type induction motor	Wound-rotor type induction motor
Construction					
Group or individual operation	Individual	Group, Individual	Group, Individual	Individual	Individual
Output power range	5~90kW	5~1000kW approx.	Above several thousand kW	Several hundred ‒ several thousand kW	Several hundred ‒ several thousand kW
Speed range	500~5000rpm	500~9000rpm	Low speed	500~1500rpm	500~1750rpm
Speed control range	1 : 20	1 : 10	1 : 100	1 : 1.5~1 : 3	1 : 2
Torque characteristics	Constant torque	Constant torque	Constant torque	Constant torque	Constant torque
Speed-torque characteristics (typical example)					
Features	● Suitable for reversible drive of single, independent motors. ● High speed drive with no relation to mains power supply frequency. ● Motor terminal voltage is sinusoidal, current is square wave.	● Suitable for irreversible drive of single or many motors. ● Good starting and low speed operating characteristics. ● Motor terminal voltage and current both almost sinusoidal.	● Suitable for large capacity, low speed motors. (several thousand kW, several rpm) ● Only frequency of about 1/3 power supply frequency is obtained. ● Motor terminal voltage and current both almost sinusoidal.	● Efficiency higher than secondary resistance control. ● Capacity of control equipment increases in proportion to speed control range. Especially economical with large capacity and narrow speed range. ● No braking torque occurs.	● Same fetures as static Scherbius. ● Speeds above synchronous speed can be obtained. ● Braking torque occurs. ● When control equipment of same capacity is used, wider speed control range than static Scherbius is possible. ● Power factor regulation possible by changing the phase of secondary power supply.
Typical applications	Machine tools, dynamometers, other industrial machinery	Rolling stock, auxialiary steel mill	Cement kilns, ball mills, paper machine drivers, main rolling mill	Extruders, pumps, fans, kilns	

4) Transistor type commutatorless motor (TR Permotron and Electronic Motor)

These motors employ transistors in place of the thyristors. Since the transistors have high frequency switching characteristics, there are especially applicable for low capacity high speed motors.

2 Variable Frequency Control Motors

These systems are based on the principle that the speed of AC motors is proportional to the power supply frequency. In this system, the firing and putting out of the thyristor rectifiers differ from those in the commutatorless motors and have no relation to the positions of the motor field poles. Therefore, it is possible to provide a common variable frequency power supply for several motors so that group operation can be performed. The torque generation principle of the AC motors is applied directly and it is possible to use synchronous or induction motors as the motors. The main significance of the operating characteristics when AC motors are used for variable frequency drive is the out-of-phase phenomenon or the over-slip phenomenon during rapid changes of the speed setting (i.e. rapid changes in the power supply frequency) or rapid load changes, the phase rotation reversing action for reversing and the power supply waveform. Because of these points, there will still be limitations in the future on the operating and control characteristics of variable frequency control motors.

1) Synchronous motors

Because synchronous motors show the out-of-phase phenomenon in respect to rapid changes in the speed setting or the load, they are unsuitable for variable speed operation by means of the frequency control system of synchronous motors in respect to such application conditions and in the case of independent operation, the previously described commutatorless motors with which there is no fear of out-of-phase phenomena should be used. However, since highly accurate open loop speed control is possible with synchronous motors by raising the supply frequency accuracy, the variable frequency control system using synchronous motors is very good for applications with small load changes at gradual acceleration or deceleration and especially for applications in which high accuracy sectional operation of several small capacity motors is performed.

2) Induction motors

Induction motors feature simple and durable construction and there is also none of the out-of-phase phenomena seen in synchronous motors. However, they are worse than the synchronous motors concerning the constant speed obtained in respect to the power supply frequency. Therefore, the group operation of several motors is limited to cases where high sectional drive characteristics are not required. In the case of independent drive, a high speed accuracy can be obtained by providing an open loop control circuit. In this case, a non-linear factor is included in the speed control loop in induction motors because the excitation current and load current are both supplied from the power supply side. Because the torque/speed relation is linear only in a certain slip range and control becomes impossible in the overslip range, it is necessary to provide a circuit such as a slip regulator for compensation when high level speed control characteristics are required, when rapid acceleration or deceleration are required or when large load changes are expected.

3) Variable frequency power supply equipment (Inverter)

Because many variable frequency power supply equipments supply square wave voltage or current, torque ripple occurs in the motor and special care must be taken in case of low speed drive. Since the current and voltage are both almost sinusoidal in the pulse width modulation type inverter and the cycloconverter included in the variable frequency control system, there is considerable improvement in the starting characteristics related to torque ripple and the operating characteristics in the low speed range. Therefore, high level operation and control characteristics can be obtained.

(1) Voltage controlled type inverter with DC link (FRENIC 1000)

This inverter has the same performance MG type variable frequency converter. It is particularly suitable in the group operation of small squirrel cage induction motors and synchronous motors. When braking is required, it is necessary to provided two rectifiers connected in reverse parallel on the power supply side or provide a braking resistance in the DC link.

(2) Current controlled type inverter with DC link (FRENIC 2000)

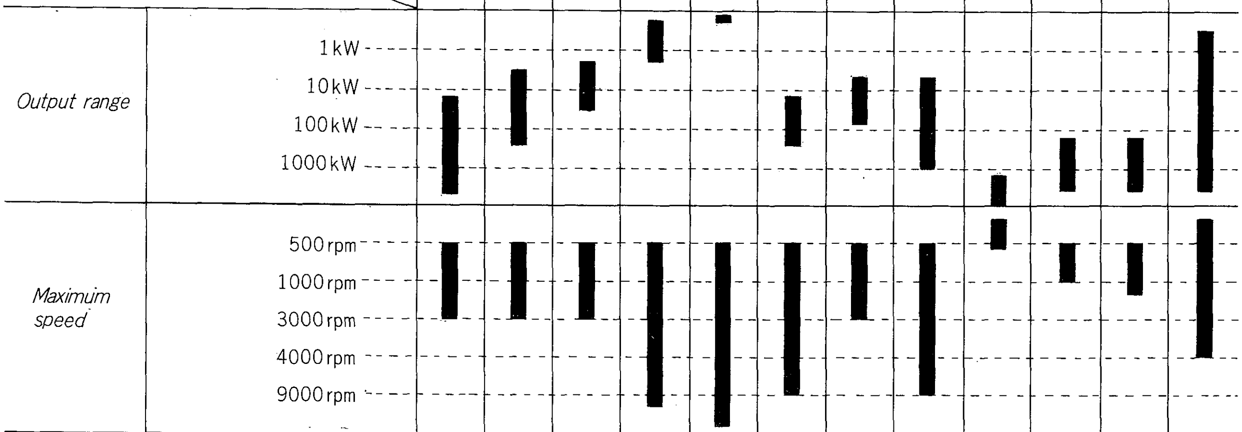
This inverter is used mainly in individual operation of induction motors and by providing a slip regulator or a voltage regulator, operation characteristics quite similar to reversible Leonard control of DC motors can be obtained.

(3) Pulse width modulation type inverter

This inverter provides an AC voltage output by cutting the DC voltage by mean of a chopper circuit and both the motor voltage and current waveforms can be sinusoidal. Therefore the starting and low speed operation characteristics are much better than in the FRENIC 1000 and FRENIC 2000, but the control equipment is rather complex.

(4) Cycloconverter

In this converter, the voltage wave of a constant frequency AC power supply is cut off by a thyristor rectifier and a low frequency output voltage is obtained by connection with this. In practice, the maximum frequency is only about 1/3 of the AC power supply frequency and its use is limited in special low speed motors because of the low power



Selection conditions \ AC variable speed motor		MC Permotron	AC Permotron	DC Permotron	TR Permotron	Electronic motor	FRENIC 1000	FRENIC 2000	Pulse width modulation type inverter	Cyclo-converter	Static Scherbius	Super-synchronous Scherbius	Thyristor Leonard
Speed control range		1 : 20	1 : 20	1 : 20	1 : 20	1 : 20	1 : 20	1 : 20	1 : 10	1 : 100	1 : 1.5 ~ 1 : 3	1 : 2	1 : 100
Speed fluctuation factor		◎	◎	◎	○	○	○	○	○	◎	○	○	◎
Rapid response		◎	◎	◎	○	○	○	○	○	◎	○	○	◎
Commutators, slip rings and brushes		Without	Without	Without	Without	Without	Without	Without	Without	Without	With	With	With
Operation efficiency		◎	◎	◎	◎	○	○	○	◎	◎	○	○	◎
Load characteristics	Constant output load	○	○	○	○	○	△	△	△	△	△	△	◎
	Constant torque load	○	◎	◎	◎	◎	◎	◎	◎	◎	○	○	◎
	Squared low speed torque load	◎	○	○	○	○	○	○	○	○	◎	◎	○
Operation characteristics	Braking torque	◎	◎	◎	△	△	△	◎	△	◎	×	◎	◎
	4 quadrant drive	◎	◎	◎	△	△	×	◎	×	◎	×	×	◎
	Frequent starting and stopping	○	◎	◎	△	△	△	◎	△	◎	×	×	◎
	Frequent reversing	○	◎	◎	△	△	×	◎	×	◎	×	×	◎
	Stable speed	△	○	○	○	○	○	○	○	○	×	×	◎
	Static torque	△	△	△	△	△	△	△	△	△	×	×	◎
Individual or group drive		Individual	Individual	Individual	Individual	Individual	Group	Individual	Individual, Group	Individual, Group	Individual	Individual	Individual, Group

◎ Most suitable ○ Suitable △ Not suitable but possible × Impossible

Table 2 Selection table for AC variable speed motors

factor from the standpoint of the system.

3. Secondary Slip Power Control Motors

Formerly there were several types of secondary slip power control systems for wound rotor type induction motors but at present, typical systems are the static Scherbius and supersynchronous Scherbius systems employing thyristor converters. As widely known, the former can only regenerate the secondary power in the power supply, but the latter can regenerate secondary power in the power supply and also supply secondary power from the power supply. Therefore, with the supersynchronous Scherbius system, operation is possible at speeds above the inherent motor synchronous speed determined by the power supply frequency and number of motor poles. This means that the number of motor poles can be selected with a certain degree of freedom when the speed range for operation is decided. When deciding the number of motor poles, it is necessary to make the most advantageous decision economically for both the motor and converter considering the load characteristics. Since the degree of freedom in selection of the number of motor pole usually increases in proportion to the motor capacity, the supersynchronous Scherbius system shows its features much better in large capacity motors. Other major features of the supersynchronous Scherbius system are thar both driving and braking torque can be generated.

IV. SELECTION OF AC VARIABLE SPEED MOTORS

The above sections have describe the various types of AC variable speed motors and their features but in order to select the most suitable system for a specific application from among these drive systems, it is necessary to understand the features of the various systems over past models and to consider the manifestations of these features to the maximum limits. When deciding general drive systems, it is essential to compare (1) the load characteristics, drive methods and required performance for the machinery to be driven, (2) the characteristics of the drive motor and (3) the reliability, maintenance, economy, etc. Normally, it is very difficult to understand all of the load characteristics and required performance of (1) and there are many cases where the decision is made in respect to experience mainly on the basis of long term operation results obtained for existing types. However, when applying AC variable speed motors for which there are comparatively few operating results, special attention must be paid to the load side characteristics and required performance which do not prerent much of problem in previous application standards and evaluation items.

Table 2 shows the characteristics of the various systems which serve as criteria in the selection of AC variable speed motors.

V. CONCLUSION

The above article has described in outline the various types of AC variable speed motors produced by Fuji Electric. The AC variable motors described here are much less in number than the existing DC motors and it is expected that as application techniques expand with gradual improvements in functions, the range of applications of such motors will expand considerably. As application evaluation for the various types are established, completely new applications should be established.

It is hoped that this article will have been of use in promoting the understanding of AC variable speed motors.