

## 10. Machine drive applications

### 10.1 Small scale system composed of synchronous generator(s) and induction motors

In power systems significantly influenced by rotating machine dynamics, time domain dynamics analysis is of great concern. Today, typical small scale power systems such as IPP's ones involve synchronous generators as the supply and induction motors as the significant part of the load. In this sub-chapter, such system is taken up.

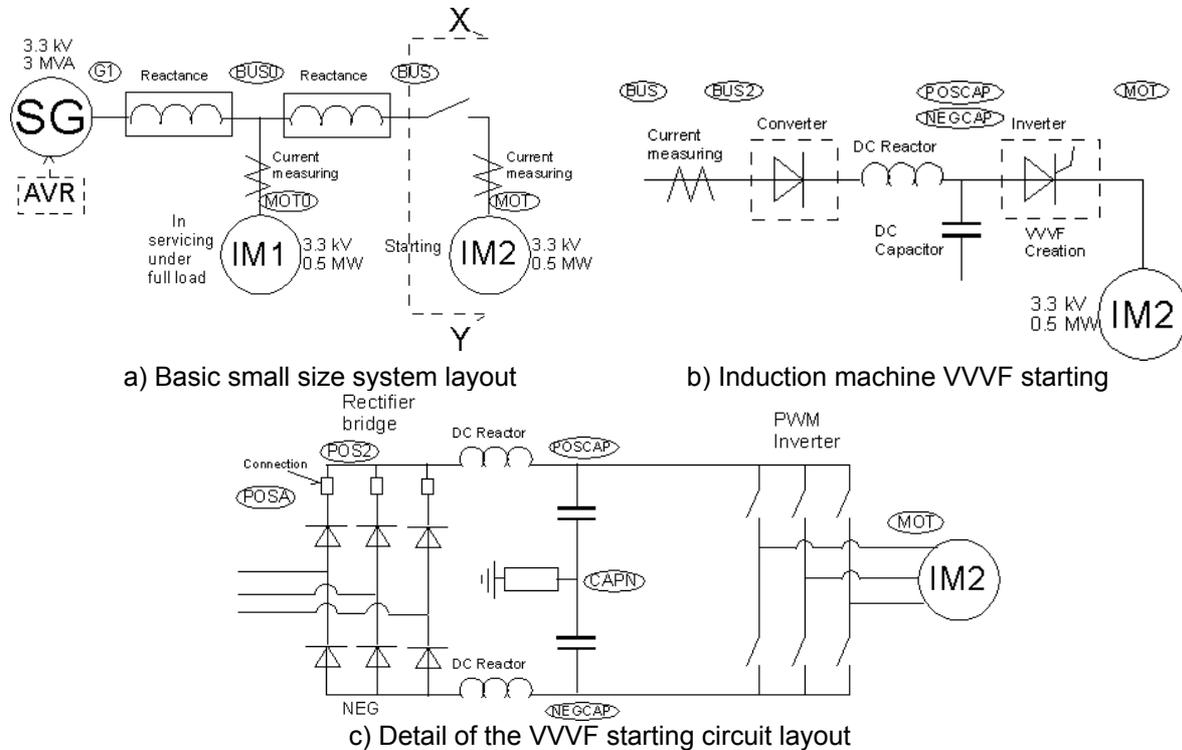


Fig. 10.1 Small size system layout with SM and IMs

A simplified such system is shown in Fig. 10.1, where the system involves a synchronous generator and two induction motors.

#### Initialisation

Firstly, the initialisation technique in ATP-EMTP for such system is to be established. In Fig. 10.1 a) the basic simplified system layout is shown where power to two induction machines are supplied by a synchronous generator. Assuming one induction motor is in full loading and the other is in very light loading conditions, the following mode of initialisation is applied as in the attached data file (Dat10-01.dat) :

- As all universal machines are to be initialised in uniform initialisation mode, slip conditions are given to the two machines.
- Voltage amplitude and phase angle are given to the synchronous generator terminal.
- No Fix Source nor Cao Load Flow option is specified, as these are not suitably applicable to universal machine by the author's experiences.
- In Fig. 10.1 a), AVR is not in service and the switch for IM2 is permanently closed.

Some calculation results are shown in Fig. 10.2, where, for convenient comparison purpose, 2P and 4P machines' variables are shown in common graphs in relevant respective scale sizes. In a) each machine's velocity is a little by little increasing during the transient calculating time interval. In b) the torques of two machines is mostly steady especially after 0.2s. A little bit of miss matching in the initialisation seems to be introduced by the calculation. Especially by the initial stage of the torques (in Fig. 10.2 b)) such phenomenon is expected. Nevertheless, the initialisation method seems to be suitably applicable to transient calculations, especially, of time interval of up to several seconds.

#### Induction motor starting

The next trial is the second motor's (IM2 in Fig. 10.1) starting from the stalled condition. As initialisation, in order to represent "stalled condition" and to satisfy "uniform initialisation mode" condition, the starting switch, which is initially open circuited, is shunted by very high ohmic resistors, i.e. very low voltage is

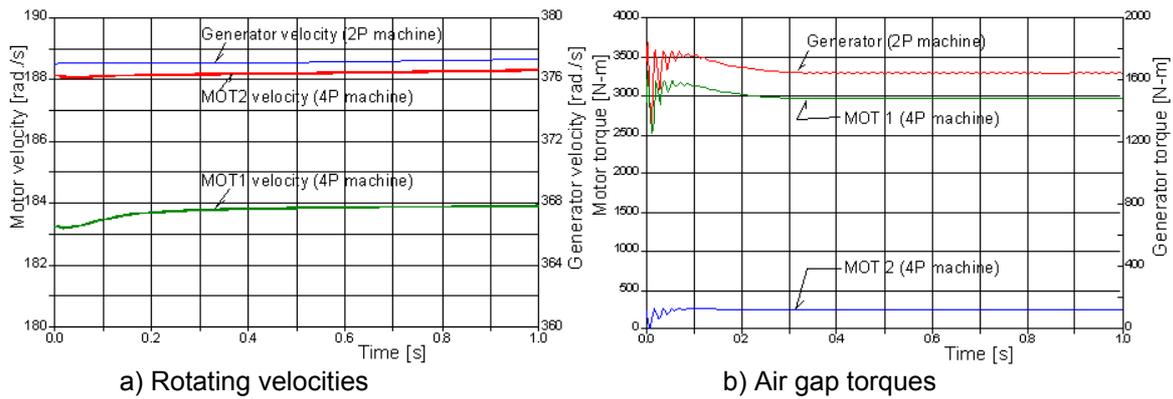


Fig. 10.2 Rotating velocities and air gap torques  
One synchronous generator (2P) & two induction motors (4P)

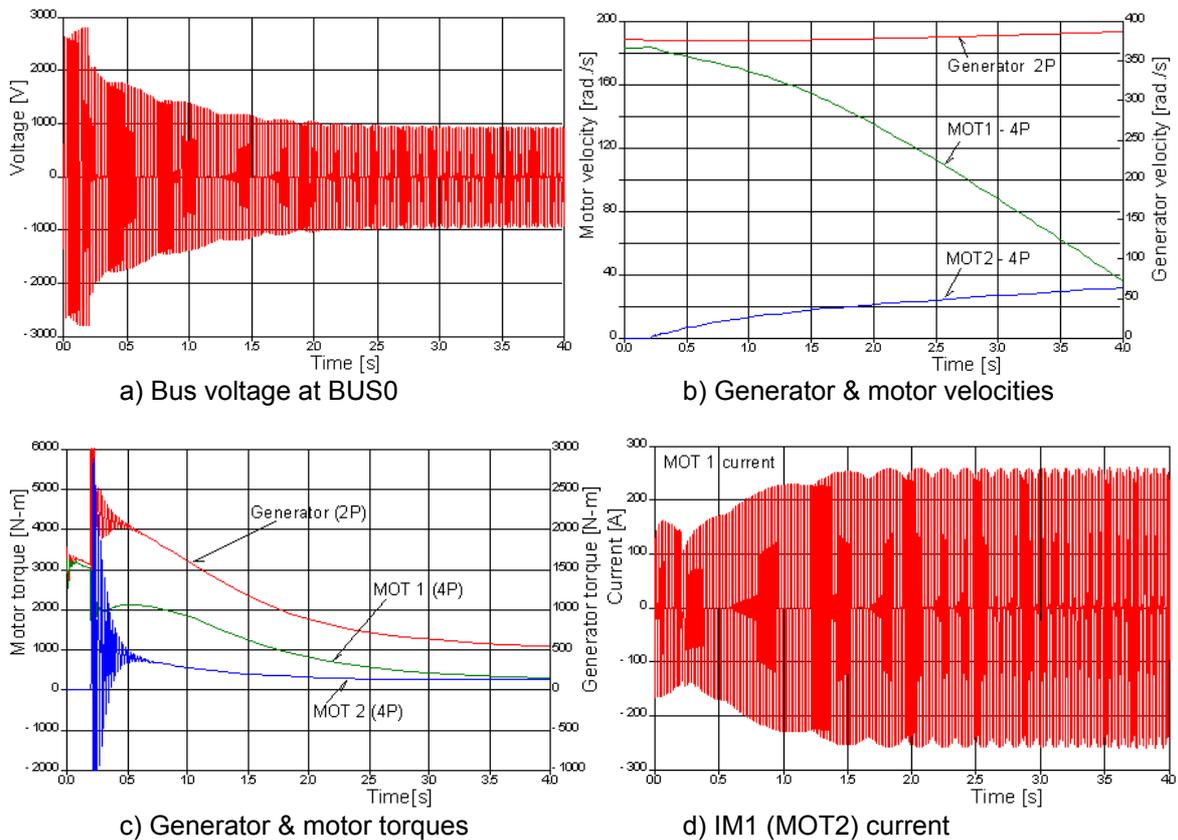


Fig. 10.3 One motor is starting during the other is in full load operation

applied to the motor, and 100% of initial slip value is given to the motor. Then the starting switch is closed. For details see the attached data file (Dat10-02.dat).

Calculated results are shown in Fig. 10.3. Shortly speaking the results show typical “voltage collapse.” In a) the bus voltage is being collapsed gradually during starting of MOT2. By the starting current of MOT2, the generator’s terminal voltage drops, so, for keeping MOT1’s torque constant, MOT1’s current increases as shown in d). The bus voltage furthermore drops. MOT1’s velocity can never be kept as shown in b), while acceleration of MOT2 is very low. By the voltage drop, the generator supplies less power, i.e. less air gap torque as shown in c), the generator accelerate gradually as in b) due to the constant mechanical input torque. As the result, MOT2 can never start appropriately in the system.

### Application of AVR

The most important requirement in the system above is to keep the voltage. AVR is the first priority for the purpose. So, let us introduce AVR to the generator. In chapter 7 (See Fig. 7.12) AVR was discussed. In this chapter, the same AVR (but without PSS) is introduced. Chapter 7 relates to very high capacity of generators, but for simplification, the same one is applied also to relatively low capacity of generator in this chapter. For details, see the attached data file (Dat10-03.dat).

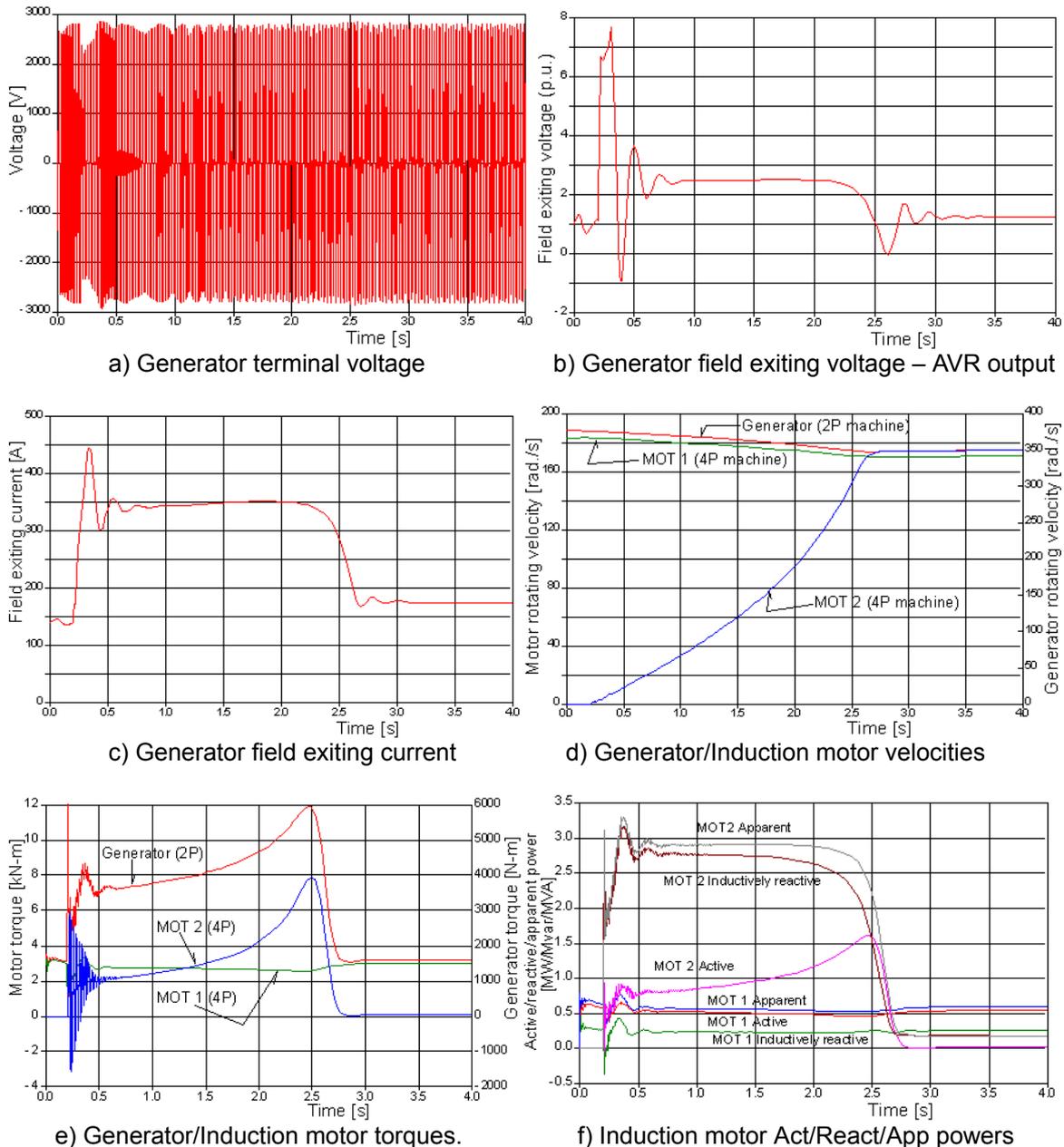


Fig. 10.4 Induction motor starting in a system supplied by an AVR furnished generator

Calculated results are summarized in Fig. 10.4. a) shows generator terminal voltage, where, though voltage drop of short time interval appears at the initial time, the voltage is kept approx. constant value. The generator exiting voltage, which is the output of AVR shows (in b)) the initial steep enhancement and the following approx. constant value of 250% of the original one during the motor starting time interval. After the start has been established, the value comes back to approx. the original value. The exiting current (in c)) shows the similar variation. d) shows the motor (MOT 2) started normally. But the system frequency, i.e. the synchronous generator's velocity, lowered a little. The generator air gap torque, shown in e), due to the enhancement of the field exiting voltage, enhanced a lot during the starting, whereas the mechanical input torque is kept

constant due to non-governor controlling. Therefore, the generator is decelerated. f) shows that induction motor consumes extremely high inductively reactive power during starting.

**Inverter controlled VVVF starting**

As shown in Fig. 10.4 f), cage-rotor induction motor’s starting consumes extremely high inductively reactive power. While, as shown in chapter 8, VVVF starting with linearly rising voltage and frequency provides highly efficient starting. For such purpose, power electronics technology, i.e. inverter, is suitably applicable. The next trial is applying such power electronics technology to the case. Fig. 10.1 b) and c) show the circuit layout applied. In chapter 9, PWM inverter is introduced, where practically any kind of AC voltage wave can be produced corresponding to the reference voltage signal wave shape. So, introducing linearly rising amplitude and frequency of wave shape as the reference wave, suitable VVVF source is realised in Fig. 10.1.

Care should be taken that PWM inverter shown in Fig. 10.1 (also in Fig. 9.7) produces relevant correct voltage for phase-to-phase, but not for phase-to-earth, i.e. zero sequence voltage component exists. On the other hand, induction machine armature coil is to be solidly earthed for automatic initialisation due to the restriction in ATP-EMTP. So, un-due current of zero sequence component may flow in the armature coil, though the current introduces little effect on the rotation of the machine. Nevertheless, the current may produce undue joule loss. To exclude such zero sequence current component, any of the following means can be applied. :

- Applying solidly-earthed-neutral type inverter.
- Inserting star-delta connected transformer for infinitive zero sequence impedance in the source side.
- Coupled reactor with very high zero sequence impedance inserted.

In Fig. 10.1, the third method seems to be most simple, so this method is applied, though this is not realistic. Fig. 10.5 shows calculation results without such consideration. Though the rotation phenomenon seems to be normal, typical un-due armature current with high zero sequence components is resulted.

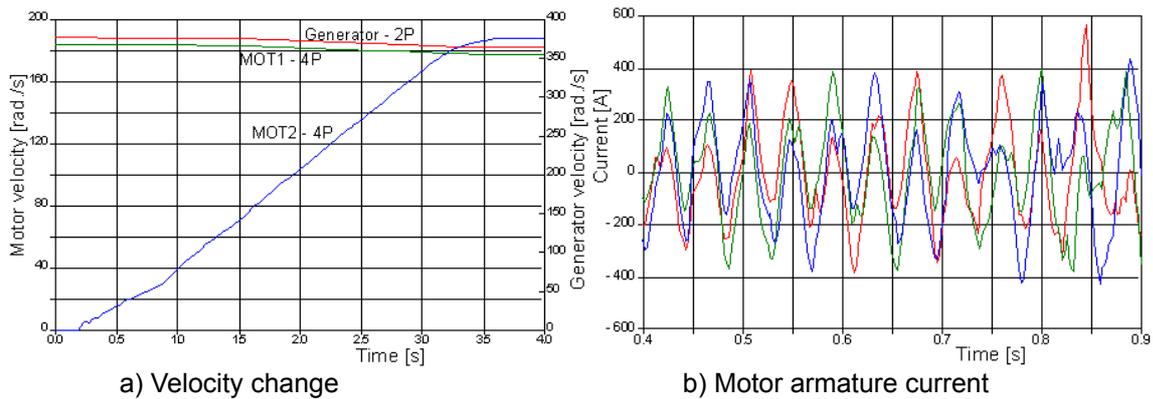


Fig. 10.5 Variables in earthed neutral system in both motor and system sides

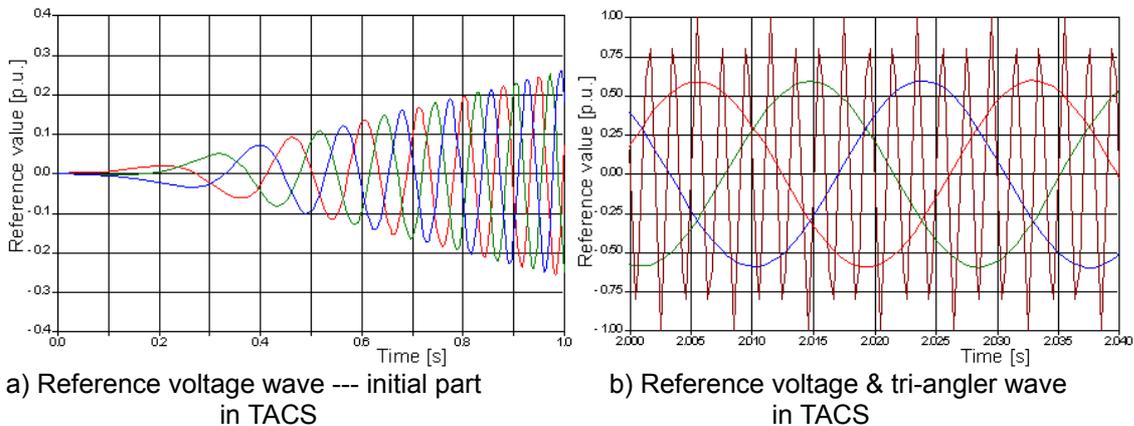


Fig. 10.6 ----- continue to the next page -----

With significantly high value of zero sequence reactance in the reactor between the source and the rectifier bridge in Fig. 10.1, and with, also, high impedance for the capacitor neutral earthing (at CAPN),

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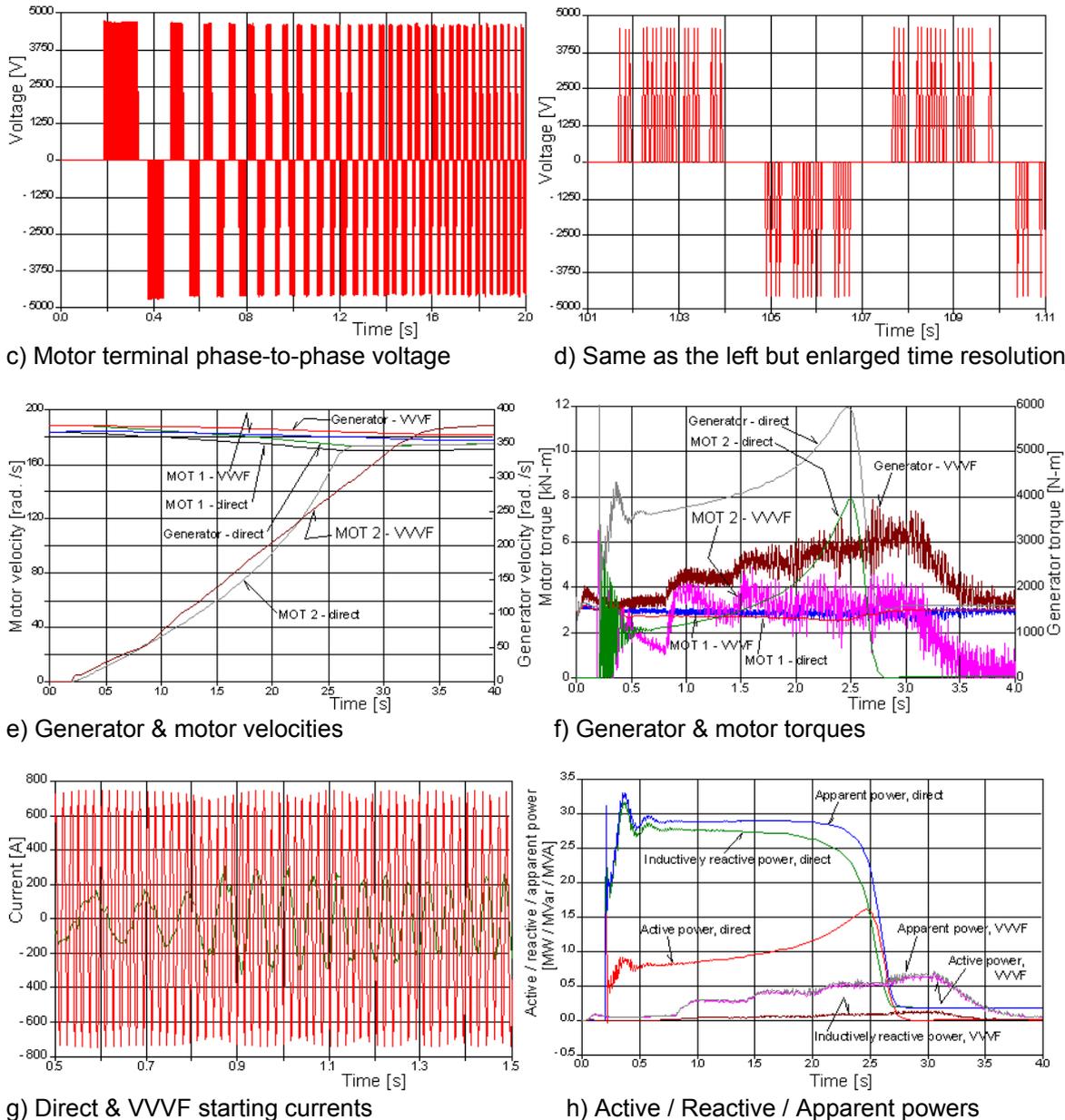


Fig. 10.6 Comparison of VVVF starting with direct starting

some calculation results are shown in Fig. 10.6. For details of the circuit parameters, compare the attached data files (Dat10-04.dat and Dat10-05.dat. Dat10-06.dat is only for fine time resolution output.). The followings seem to be noted for each figure. :

- 3-phase reference voltage wave shape is shown for the first 1 second, the amplitude and frequency of which are linearly rising to the certain specified values.
- Tri-angular carrier and 3-phase reference voltage wave shapes in TACS are shown for the intermediate time. By the comparison of the waves the gate signals to the inverter valves are produced in TACS for producing correct phase-to-phase voltage to the motor. For details, see sub-chapter 9.3.
- Motor terminal phase-to-phase PWM inverter output voltage is shown for the first 2 second.
- Same as c), but in very fine time resolution representation for the intermediate time interval.
- Generator and motor velocity changes by VVVF starting are shown in comparison with direct starting ones. By similar starting performances of both cases, VVVF brings far less influence to the system, i.e. less descending in synchronous machine velocity/frequency.

- f) Time-integration of the starting motor's torque, i.e. the area below the torque-vs.-time curve is to be equal for both cases. Nevertheless, generator's torque curves shown great difference between two. Significant electrical loss is to be produced, most provably by the winding's joule loss.
- g) Instead of the mostly similar starting characteristics by both, the starting motor currents show great difference each other. This is the most typical feature of VVVF starting of induction machine, i.e. highly efficient starting.
- h) Active, inductively reactive and apparent powers during starting by both direct and VVVF startings are compared in the figure. (For the output of VVVF starting, due to non-symmetrical three-phase variables creating lot of fluctuations, the outputs are smoothed in TACS.) Great energy saving in VVVF, especially for starting is significant. Also little reactive power is consumed. Within the inverter circuit, reactive power can be produced.

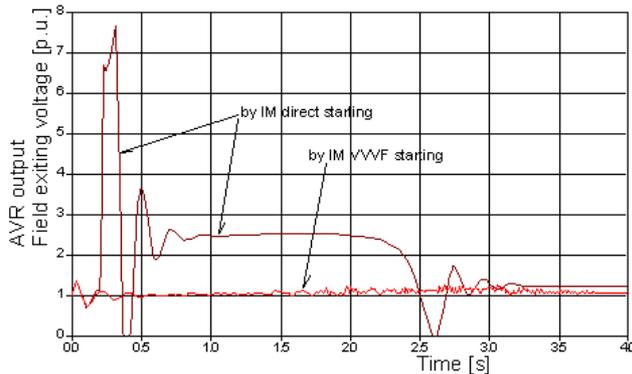


Fig. 10.7 Field exiting voltage comparison

Fig. 10.7 shows generator's field exiting voltages by both direct and VVVF starting, both are controlled by AVR. By VVVF starting, high response of AVR seems to be almost unnecessary.

VVVF controlled cage-rotor induction motor seems to be applicable for various variable speed controlled usage.

**Attached data files for the sub-chapter:**

- Dat10-01.dat : Initialisation of a system composed of one synchronous generator and two cage-rotor induction motors
- Dat10-02.dat : Ditto system, but one of the motor is directly starting, resulting in voltage collapse
- Dat10-03.dat : Ditto system but the generator is furnished with highly sensitive AVR, resulting in successful starting
- Dat10-04.dat : Ditto system but the starting motor is driven by VVVF inverter source, the neutral potential of which is restricted, resulting in un-due zero-sequence motor current.
- Dat10-05.dat : Ditto system but VVVF inverter source side is in neutral floating condition, inserting high zero-sequence reactance of reactor between the system and the converter-inverter
- Dat10-06.dat : Ditto, but only for very fine time resolution of output usage

## 10.2 Cyclo-converter driven synchronous machine

Some rolling machines in iron industry are driven by synchronous motors, the power sources of which up to today are cyclo-converters. Therefore, as the next example, cyclo-converter driven synchronous machine is taken up. In addition, comparison with inverter driven system will be shown.

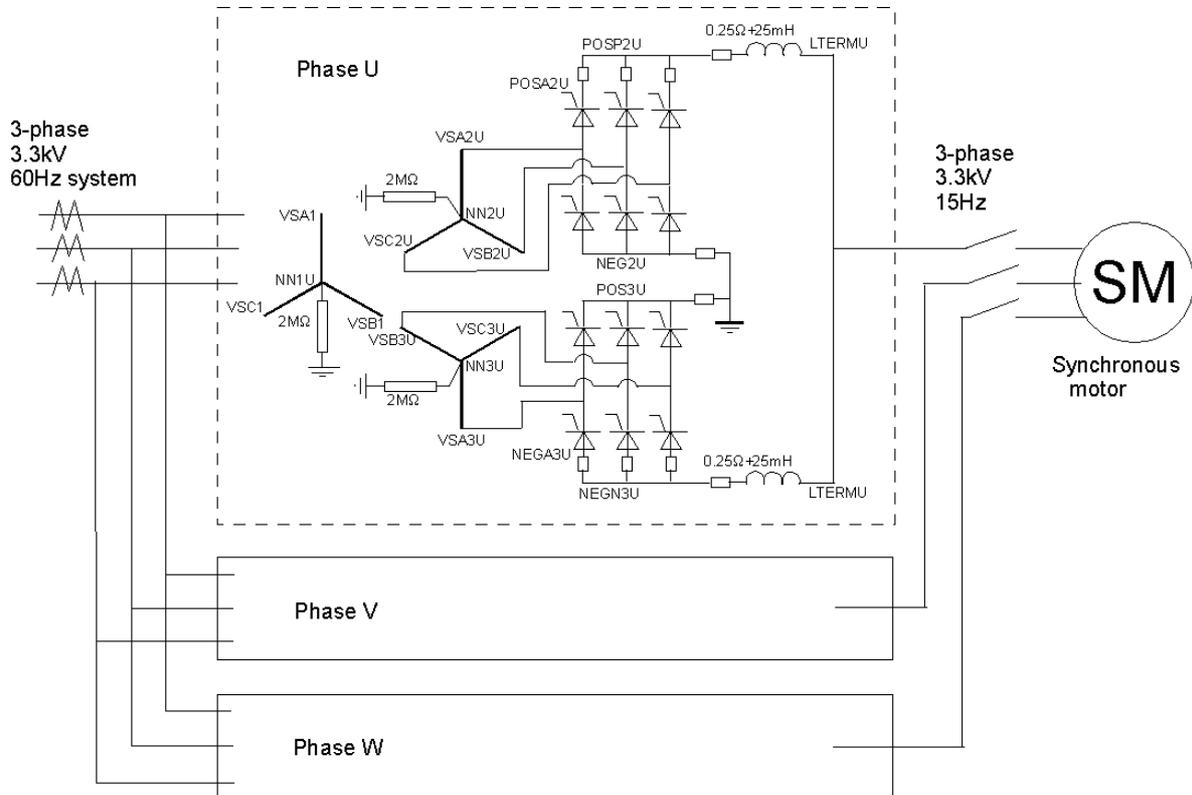


Fig. 10.8 Cyclo-converter driven synchronous motor circuit layout

Fig. 10.8 shown circuit layout applied. The followings are to be noted. :

- In sub-chapter 9.4, detail of one-phase cyclo-converter is explained. Three of the same converter systems are applied for driving 3-phase synchronous machine, the ratings of which are 3.3kV, 15Hz, 1MVA, 6P, etc.
- Transformer secondary side (converter valve side) is to be non-solidly earthed condition in each phase. Therefore, 2 sets of high-ohmic resistor earthed star windings are applied for each phase as shown in the figure. The primary side could be a common one set of 3-phase winding. In the case, for simplification, three sets of star connected windings are applied for 3-phase.
- 3-phase reference voltages are to be given to 3-phase converter controlling (in TACS).
- For initialisation very fine tuning is required, especially between the reference voltage and the initial machine terminal voltage, regarding the amplitude and phase angle.

The first example is to apply **sudden mechanical load** to the rotating motor in almost no-load condition. The initialisation and transient calculation process applied is (as the most simplified one):

- Initially the motor is disconnected from the cyclo-converter.
  - Automatic initialisation is highly recommended for synchronous machine. The motor is rotating in very lightly loaded generator mode, i.e. giving the terminal voltage with the relevant frequency, and high-ohmic resistor is connected to the terminal of the machine for the purpose of easy and proper initialisation.
  - As the next step, the machine is connected to the cyclo-converter source for motor operation.
  - Then afterwards, sudden mechanical load is applied such like in rolling machine by means of TACS.
- For details, see the attached data file (Dat10-12.dat).

Some calculation results are shown in Fig. 10.9.

- a) As details are shown in chapter 9, cyclo-converter output voltage involves certain amount of high-frequency components.
- b) Synchronous motor current, due to reactance components in the circuit, does not involve significant

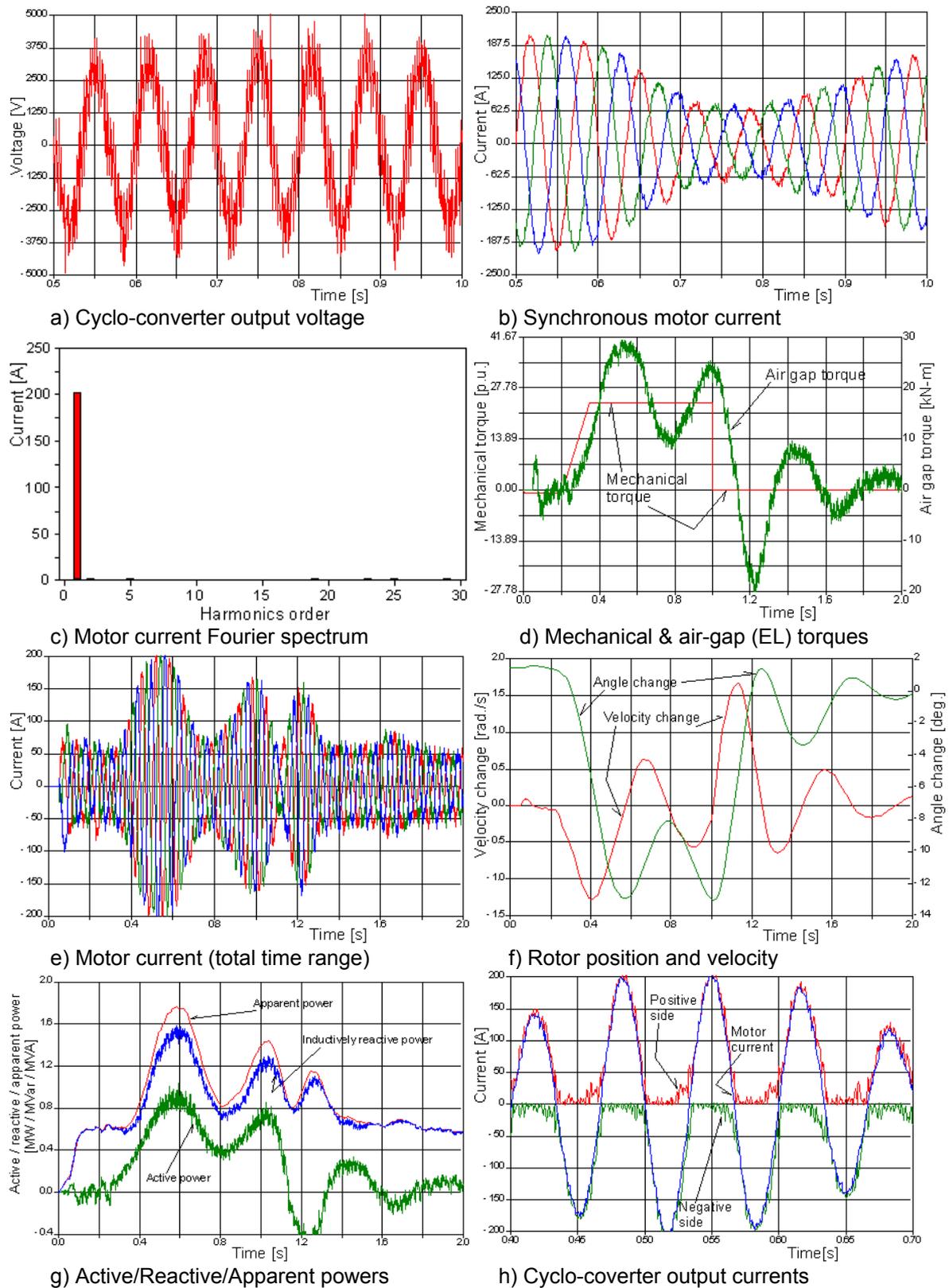


Fig. 10.9 Cyclo-converter driven synchronous motor ----- continuing to the next page

amount of high-frequency component. The current amplitude changes a lot depending on the load condition.

- c) Fourier spectrum of the current clarifies less high-frequency component.

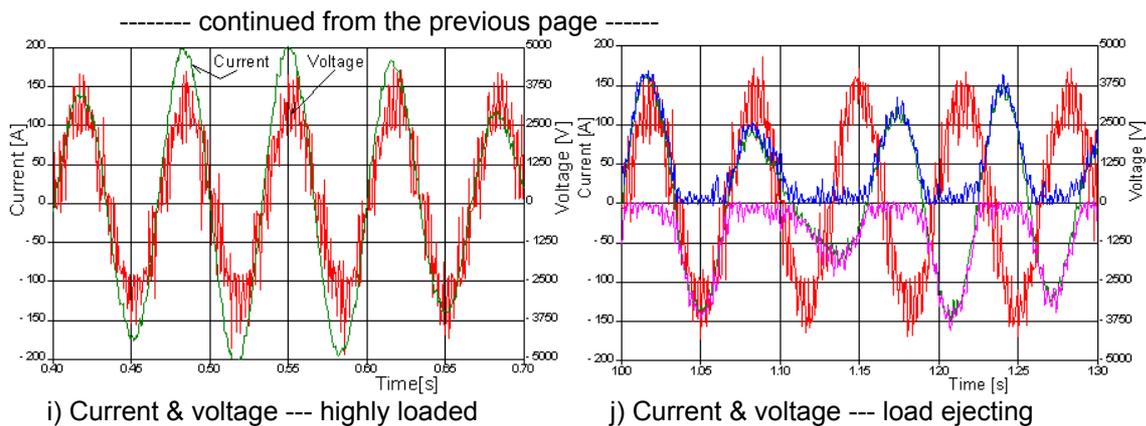


Fig. 10.9 Cyclo-converter driven synchronous motor

- d) Suddenly applied mechanical torque (TACS controlled) and calculated air gap torque are shown. Due to sudden application and ejection of the torque, significant swing of the air gap torque is produced.
- e) By the swing, the motor current (in total time range) changes a lot.
- f) The swing is observed in, also, rotor position angle and velocity.
- g) As shown in chapter 9, cyclo-converter driven system consumes a lot of reactive power. In many cases, compensation facilities (capacitor bank) are required.
- h) Positive and negative polarity converter bridge work well at turning over.
- i) At highly loaded instant, the power factor seems to be high. Fig. g) clarifies this.
- j) At the load eject instant, the current drastically changes, especially, in phase angle. Turning over between the positive and negative bridges seems to be suitable from the current wave shape.

In the next example, **quick starting of cyclo-converter driven synchronous motor** is taken up.

In chapter 6 --- Appendix 6.2, synchronous machine starting as induction machine is demonstrated, where, to represent short-circuited field coil, very low voltage is generated while initialisation. Now, in this case, properly excited synchronous machine is to be driven by cyclo-converter. Then, the following initialisation process is to be applied. :

- The machine's initial velocity is to be as low as possible within restriction of ATP-EMTP synchronous machine initialisation menu. In this case, 0.5 Hz is applied.
- The motor-internally generation voltage is to be proportional to the velocity, i.e.  $0.5 / 15 = 0.033$  times of the rated voltage where the rated frequency of the motor is 15Hz.
- The applied voltage is to correspond to the machine induced voltage. So, cyclo-converter output voltage is to be linearly rising frequency and amplitude one, corresponding to linearly rising velocity.

For details of the input data file, see attached data file (Dat10-13.dat)

Some calculation results are shown in Fig. 10.10.

- a) The command (reference) velocity, which is the base of the frequency and the voltage amplitude, and the resultant calculated motor velocity (represented in electrical angular velocity) are shown. Certain mitigation to the velocity change, for smooth mechanical response, is applied applying s-block function in TACS. See the attached data file (Dat10-13.dat). A little bit of un-stability in the motor velocity, especially in higher velocity region, is observed.
- b) 3-phase reference voltage wave shapes. As shown in chapter 9, cyclo-converter output voltages correspond to these wave shapes. Linearly rising amplitude and frequency of waves are represented.
- c) Cyclo-converter created applied voltage and motor current of 1-phase is shown for total time range. The current amplitude is not constant.
- d) Detail of the initial part of figure c) is shown, where, mainly reactive current flows.
- e) Detail of figure c) when higher torque outputting. The power factor seems to be higher, at least around the motor part. For the total driving system circuit, detail will be shown later.
- f) Ditto, but for after started and rotating by no-load. The power factor seems to be low and the current amplitude, also, is low.
- g) The motor air gap torque is shown in contrasted with the velocity. Un-stability is clearly shown, most probably due to mechanical and/or electrical parameters. For more smooth response, farther more

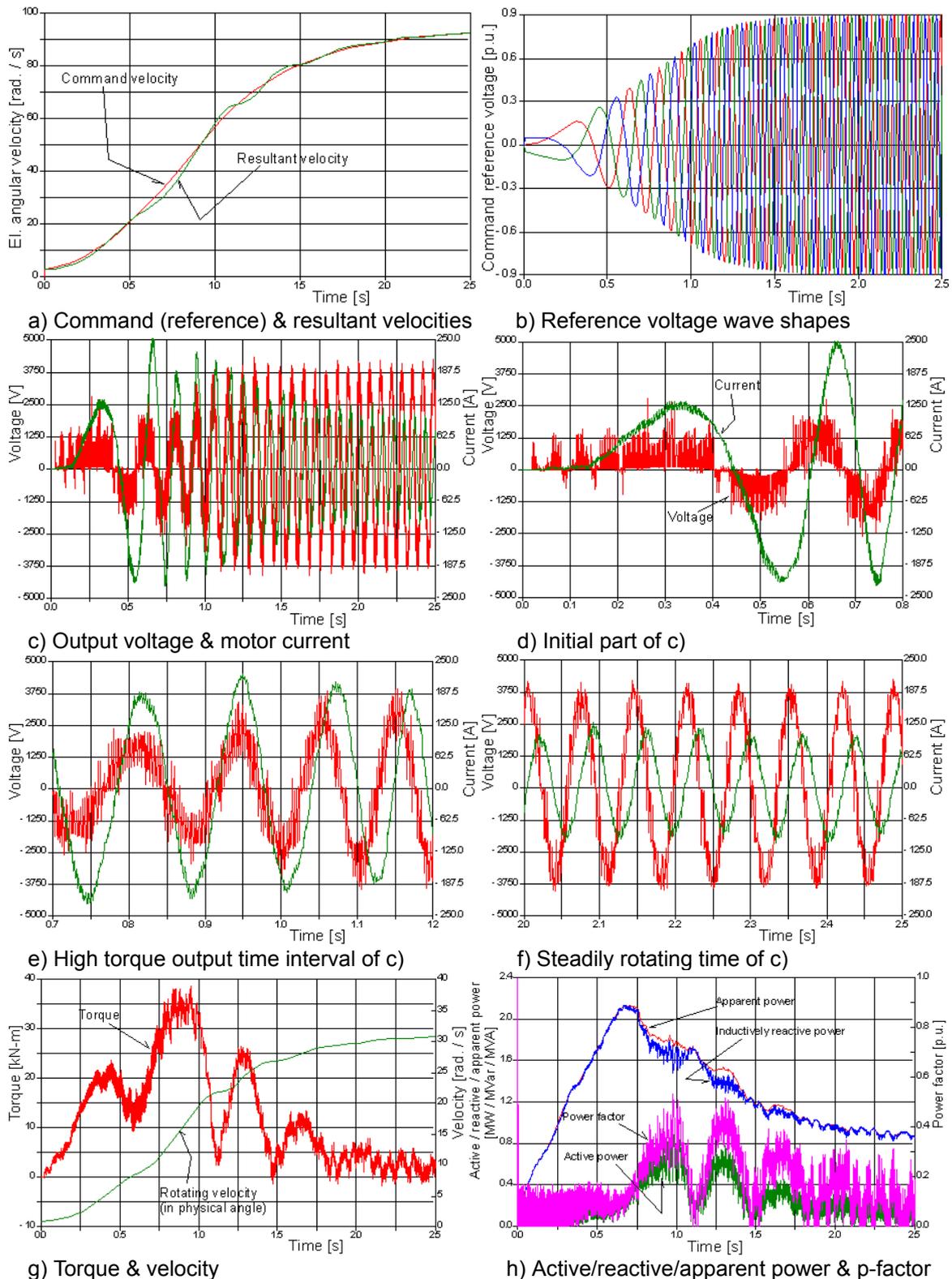


Fig. 10.10 Quick starting of cyclo-converter driven synchronous motor

stability study seems to be necessary. Powerful feed back control system may be effective.

- h) Active power, reactive power, apparent power and power factor measured at the power frequency inputting point are shown. At  $t = 0.9$ s, when the motor torque is highest, the power factor is still not so high, i.e. around 0.3p.u. For such reason, compensation facilities (capacitor bank) are installed by some cyclo-converter systems.

**Comparison with inverter driven system** will be shown in the following cases.

Firstly, “sudden mechanical load application” is introduced to inverter driven system. In the inverter driven system, mostly equal to one in the previous sub-chapter is applied, i.e. the inverter circuit layout in Fig. 10.1 c) is applied. As for the detail, see attached data file (Dat10-15.dat). The reference voltage to control inverter output is identical to one in the cyclo-converter.

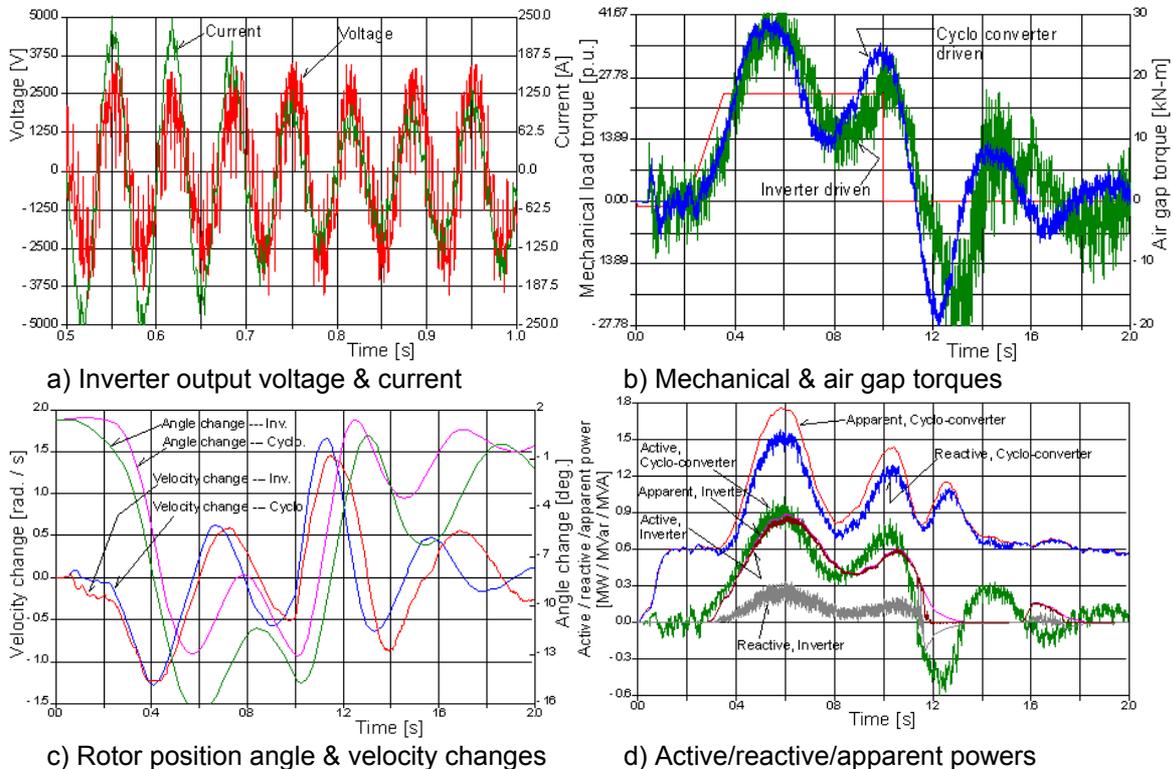


Fig. 10.11 Comparison of inverter with cycle-converter

Typical comparisons between two are shown in Fig. 10.11.

- Inverter output voltage and motor current for mainly heavy mechanical loading time interval is shown. The power factor seems to be very high. By no-loading time interval (not shown), on the other hand, the power factor at the motor input is very low.
- By sudden mechanical load torque, air gap torques by both case are compared. Both are mostly identical, i.e. the responses are almost equal by both source circuits.
- Small difference is observed as for the rotor position angle between by two sources. Though the reference voltage wave is identical each other, small difference may be introduced between two created voltage wave shapes. The cause might be the finite time step length of controlling.
- Great difference is shown in the power frequency source supplying inductively reactive power between two source circuits. By inverter, power frequency side reactive power is negligibly small. As written in a), for no mechanical load time interval (especially after 1.5s) the motor consumes some reactive power, nevertheless, the power frequency side reactive power is negligible. Inverter itself supplies reactive power from the capacitor in the circuit.

Note:

Calculated power outputs by inverter are smoothed by s-block function in TACS. As the calculation principle is based on balanced three-phase variables, such mitigation is to be applied for variables with high frequency components.

In the next, **quick starting by inverter driven** is taken up. The reference velocity/voltage condition to control the inverter is identical to cyclo-converter case. Great care should be taken that, by inverter, especially for very low velocity of condition, the total system tends to be unstable. The phenomenon is observed in Fig. 10.12 d). The cause of the un-stable seems to be mechanical and / or electric circuit condition of the system. Detail has not been clarified by the author. In the following exercise, the resistance value in the reactor between the inverter and the motor is doubled compared to the case by cyclo-converter. For detail, see attached data file (Dat10-15.dat). Otherwise, the motor performs un-stableness. The reader should try the case by “Dat10-1X.dat”, where the resistance value is equal to

the original one.

Some calculation results (with the increased resistance) are shown in Fig. 10.12:

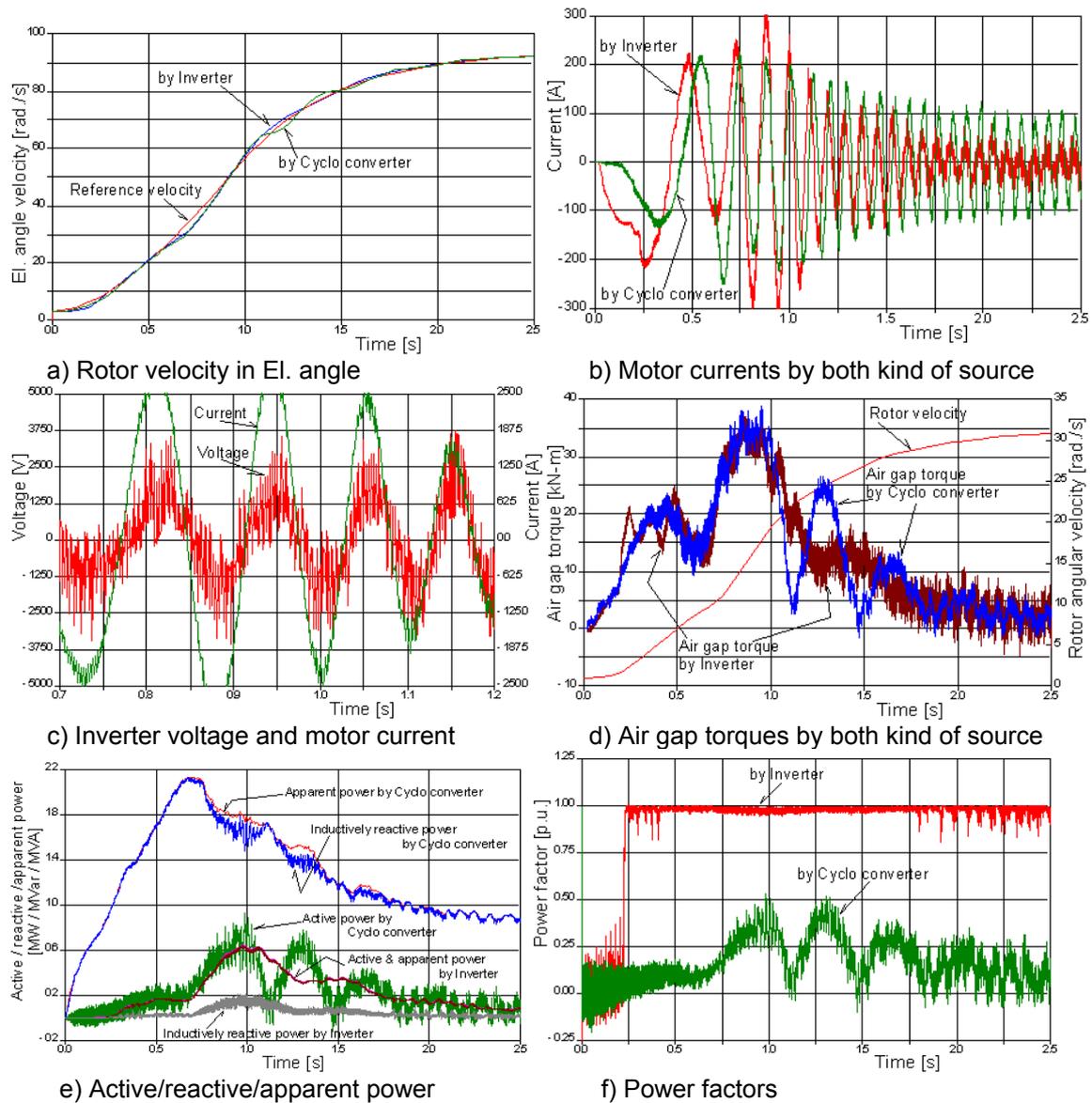


Fig. 10.12 Inverter driven synchronous motor ---- quick starting

- Mostly identical starting characteristics are obtained by both (inverter and cyclo-converter) source driven systems, though in inverter, the connection reactor's resistance value is doubled.
- Motor input currents are compared between both cases. By identical reference voltage conditions by both, the actual and effective output voltage may more or less differ each other, as details of the voltage wave shapes, including high frequency components, are different by each other.
- When the maximum torque is created, the motor current is of very high power factor such like in cyclo-converter driven case. After establishing the velocity (not shown), however, the motor current power factor is low. Still the power factor of the power from the power frequency source system is high as shown later.
- From the air gap torque characteristics, the following is clear. Inverter driven tends to be unstable in very low velocity region but stable in higher velocity region. Cyclo-converter driven tends to be opposite, i.e. stable in low velocity and un-stable in higher velocity. As the countermeasure for mitigation, powerful feed back system could be applied.
- Active, (inductively) reactive and apparent powers are compared between both systems. Inverter system's high power factor feature is remarkable.
- In power factor graph, also, the tendency is clearly shown. By inverter, power frequency source side

power factor is always approx. 100%. While, by cyclo-converter, the power factor is only more or less than 20%. By inverter, though the motor current power factor is not always high, the power frequency side one can always be high. This means inverter can provide reactive power by itself. On the other hand, by cyclo-converter, even though the load current power factor is high, power frequency side power factor can never be high enough due to the frequency converting principle.

As for cyclo-converter system with relatively low const, low power factor in consuming power, necessity of capacitor bank, limitation in output frequency, and as for inverter system with higher cost, high power factor, non-necessity of compensation, possibly higher output frequency, not only qualitative but also quantitative comparison could be exercised by ATP-EMTP simulation, such as shown above.

**Data files attached:**

- Dat10-11.dat: Cyclo-converter driven synchronous motor is initialised. Firstly it is in service as a no-load generator, and then cyclo-converter source is connected so as to motor operation.
- Dat10-12.dat: Ditto, but sudden mechanical torque is applied. The torque is suddenly dropped a little later time.
- Dat10-13.dat: The synchronous motor very quickly starts from stalled condition by VVVF output of the cyclo-converter.
- Dat10-15.dat: The same synchronous machine operating condition as Dat10-12.dat case, but instead of cyclo-converter, diode-bridge rectifier and PWM inverter are applied. The reference voltage to control the inverter is identical to in Dat10-12.dat case.
- Dat10-16.dat: The machine's quick start, same condition as in Dat10-13.dat, but via PWM inverter. In the case, for the mitigation of violence in the low velocity region, synchronous motor side resistance in the reactor is doubled compared to Dat10-13.dat case.
- Dat10-1x.dat: Ditto, but the resistance is in the original value. Some instability occurs in the low velocity region.



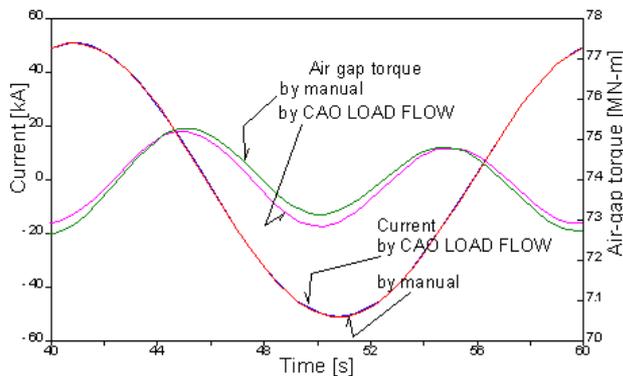


Fig. 10.14 Precisely tuned generator's current and air gap torque compared to Automatic

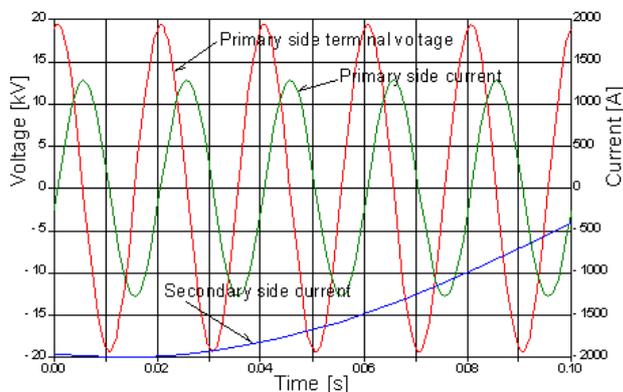


Fig. 10.15 Initial stage of the fly-wheel generator  
--- Currents are in generator direction ---

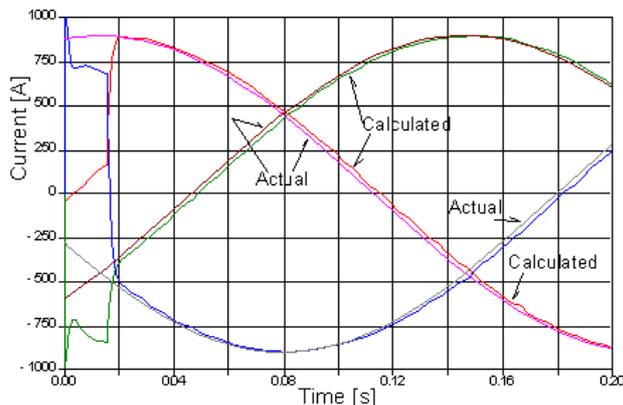


Fig. 10.16 Check of the secondary current calculation algorithm by comparing the actual and the calculated reference current

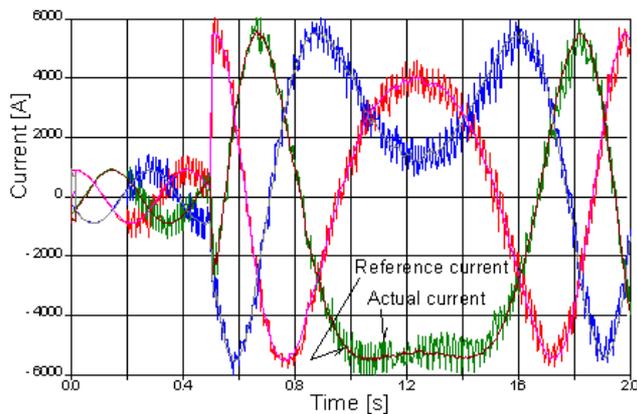
In the next step, excluding CAO LOAD FLOW option and applying the above obtained voltage amplitude and phase angle to the generator terminal, calculation is to be done. Very fine and precise tuning may be necessary, especially for the phase angle. For details, see Dat10-22.dat. By the calculation, the identical result with the former automatic initialisation case is obtained. Please compare both calculation results. Fig. 10.14 shows some examples. Small amplitude of ripple in the air gap torque is due to the asymmetry of the transmission line (non-transposed).

In the third step, the fly-wheel generator is to be initialised. As shown in Chapter 8 (final part before Appendix), doubly-fed machine is well initialised by introducing the primary side terminal voltage condition, slip value and secondary side current condition. The primary side voltage condition is obtained from the bus voltage via the step up transformer (Fig. 10.13). Initial slip value is selected to 5% as, due to the primary stage of excess energy in the power system source part in transient stability phenomena, lower velocity seems to be appropriate to absorb the excess energy. Setting the fly-wheel initial condition as capacitor mode, by very fine tuning of the secondary current condition, the machine is well initialised, see attached data file (Dat10-23.dat). Some results are shown in Fig. 10.15. The main flux magnetising current is supplied from the secondary side, so the amplitude of the secondary side current is higher. 2.5 Hz (corresponding to 5% of slip) of secondary side current appears. In the case, the secondary side is supplied by a fixed current source (2.5Hz).

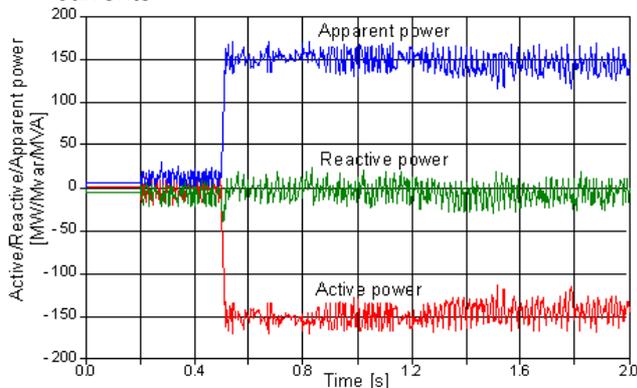
The forth step is to investigate the UM controlling reference current calculation algorithm shown in Fig. 8.9 and 8.11. For details, see Dat10-24.dat attached. Typical result is shown in Fig. 10.16, comparison of the actual (from outside source) and the calculated reference current which is to be applied to control the current regulated inverter. The inputting active/reactive power for the calculation basis is equal to the actual one. The difference between two is negligible though, due to mitigating the fluctuation in the calculated reference current, small delay-time is introduced. Anyhow, the calculation algorithm seems to be quite agreeable for the purpose.

Then, activating the inverter, the fly-wheel generator's rotor is energised by the output current of the inverter. As shown in Sub-chapter 9.5, the current regulated inverter output current is to be close to the input reference current. Therefore, applying the calculated reference current by the above shown calculation algorithm, the fly-wheel produces the target output power, the rotor being energised by the current of the inverter.

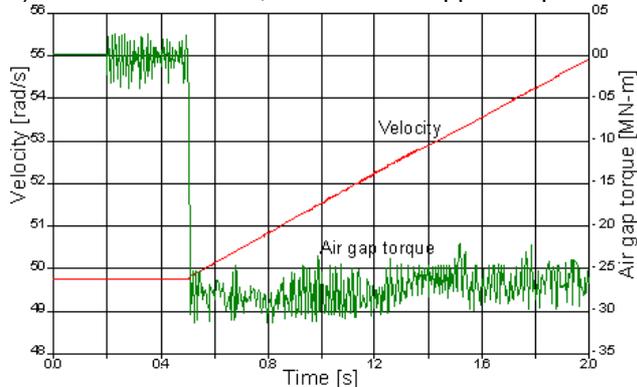
For checking the basic fly-wheel generator output power is controlled to be: (For details, see Dat10-25.dat)



a) Inverter activated, reference & actual fly-wheel currents



b) Calculated active, reactive and apparent powers



c) Velocity & air gap torque

Fig. 10.17 Activating inverter to drive fly-wheel generator

Then, the next subject is fly-wheel's proper power controlling energised by the output current of the inverter. The synchronous generator's AVR/PSS, which is the most powerful mean to enhance the transient stability, is generally controlled applying the generator's state, i.e. the terminal voltage, output power, etc. Fly-wheel generator may not be installed close to the synchronous generator. Moreover, plural synchronous generators may be covered by fly-wheel generator(s). Therefore, applying information directly regarding the synchronous generator may not be convenient. As mentioned at the top of this sub-chapter, information regarding the voltage at the relevant bus close to the fly-wheel generator seems to be mostly applicable and realistic for the purpose.

As the most direct relevance between the synchronous generator's disturbance and the bus voltage, the voltage frequency change seems to be applicable for the input of the inverter controlling. Fortunately, we can use FREQUENCY METER in TACS of ATP-EMTP. So, at first the frequency meter should be checked during disturbance regarding transient stability (during 3LG & 1 circuit of the transmission line

- Initially low inductively reactive output power
- At 0.2s, the rotor input current is switched over from fixed source to the inverter.
- At 0.4s, the fly-wheel output is increased to -150MW (active power absorbing, i.e. motor mode).
- Up to 2s the calculation is continued.

Fig. 10.17a shows the reference current to control the inverter and the machine rotor actual current (inverter output). Well working of the inverter and well driving control of the machine are expected. At around 1.2s, the rotation of the current is reversed, i.e. the velocity crosses the synchronous speed (52.36 rad/s, see Fig. 10.17c below).

Fig. 10.17b shows machine generating powers which are calculated from the terminal voltage and outgoing current. The active power is kept constant to be -150MW, though some fluctuations exist due to the inverter switching. The reactive power is negligibly small accordingly. Both powers are kept to the input condition. (See PP and QQ values in TACS of the data file.)

By absorbing active power at 0.44s, the machine begins to accelerate from 49.74 rad/s (corresponding to +5% of slip) up to approx. 55 rad/s (approx. -5% of slip) at 2s. Very precisely speaking, the acceleration rate is to be inverse proportion to the velocity due to constant active power value applied. The air gap torque is to be the same relationship. In Fig. 10.17c, the air gap torque shows gradual decrease in the value by the increase of the velocity.

Some fluctuation also exists due to the inverter switching.

Summing up the above, the fly-wheel generator connected to the source side of the one generator vs. infinite bus system seems to be well appropriately systematised and initialised. Introducing active and/or reactive power value to the inverter control terminal, the fly-wheel outputs/absorbs power with changing the velocity.

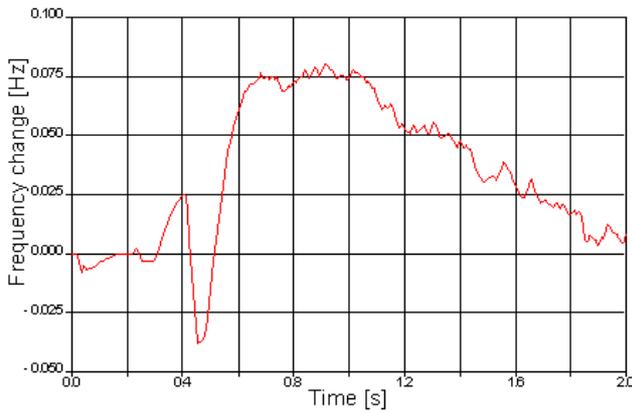


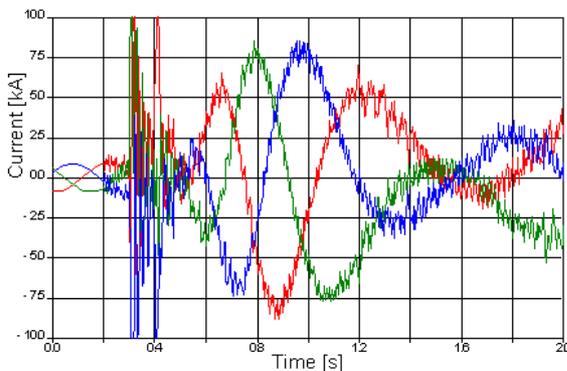
Fig. 10.18 Bus voltage frequency change during 1LG --- 1cct opening

opening).

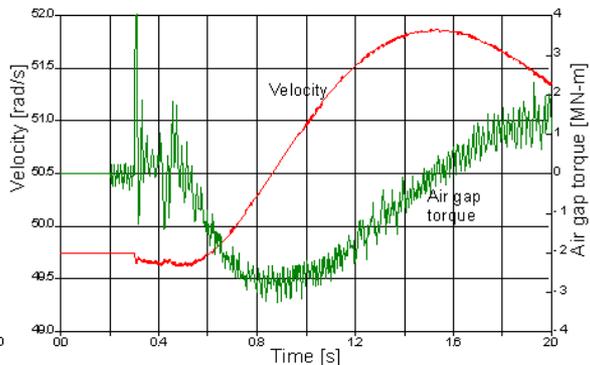
Applying FREQUENCY METER to the bus voltage where the fly-wheel generator is connected to, and after some mitigating processes in the calculation, Fig. 10.18's result is obtained. For details of the calculation, see Dat10-26.dat attached.

Due to the sudden change in the voltage during 0.3s --- 0.4s (3LG, Fault clearing and 1 circuit opening), the rapid frequency change in this time interval may be better to be excluded. However, rather steady frequency change output is obtained and suitable application to control the flywheel generator is expected.

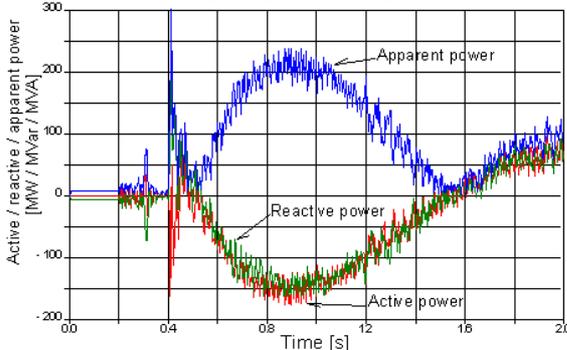
**Fly-wheel activity in transient stability**



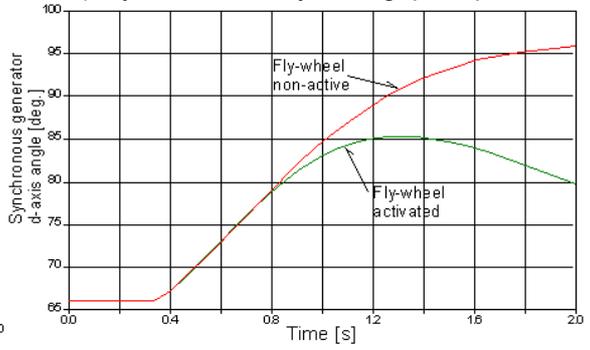
a) Rotor energising current by inverter



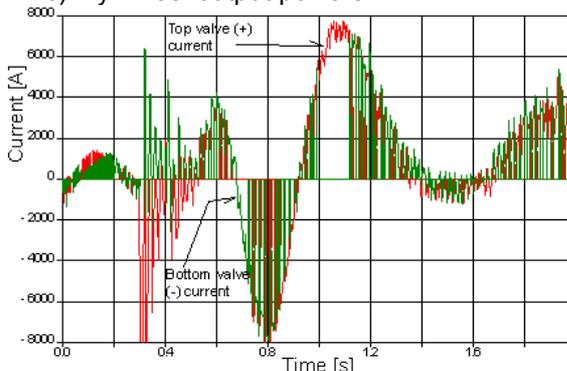
b) Fly-wheel velocity & air-gap torque



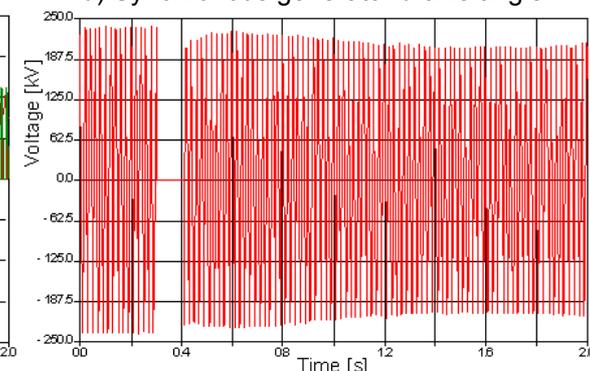
c) Fly-wheel output powers



d) Synchronous generator d-axis angle



e) Top & bottom valve switch-over current



f) HV bus voltage

Fig. 10.19 Fly-wheel generator activity in transient stability enhancement

### enhancement

In the first trial, both active and reactive power outputs of the fly-wheel generator are set to be equal and proportional to the frequency change of the HV bus voltage, i.e. by increase of the frequency, the absorption of the active power and capacitively reactive power increase. Thus, the synchronous generator's acceleration is expected to be damped. The maximum power of the fly-wheel generator is set to be approx. 200MVA, i.e. 200% loading due to short time interval. Some results are shown in Fig. 10.19.

- Except the violent transient interval (3LG & clearing), fly-wheel rotor (secondary coil) current is well appropriately supplied from the inverter.
- According to the bus voltage frequency change (Fig. 10.18) and along the vector control algorithm, the fly-wheel is driven to absorb power, enhancing the velocity, which is shown in Fig. 10.19b.
- The figure shows the powers are well controlled. The same value of active and reactive powers is shown.
- The synchronous generator's d-axis angle (swing) during the transient is damped by the function of the fly-wheel. Due to the relatively low power output of the fly-wheel generator (as for active power, approx. 13% of the synchronous generator's), the damping rate is limited.
- The figure shows top (plus side) and bottom (minus side) valve currents in a certain phase of the inverter. For certain time interval only one side valve is ON. This means the DC source voltage is critical and can never be lower.
- The HV bus voltage is lower during the swing. Therefore, according to equation 7.1 in chapter 7, the transmitting power is lower, resulting in excess source side energy. Absorbing higher capacitively reactive power to enhance the voltage, further damping of the swing may be expected.

### Active/reactive power effect

In the next case, mainly active power only is absorbed by the fly-wheel with approx. equal value of the maximum apparent power to the previous case. In TACS of the data file, changing the coefficients of the

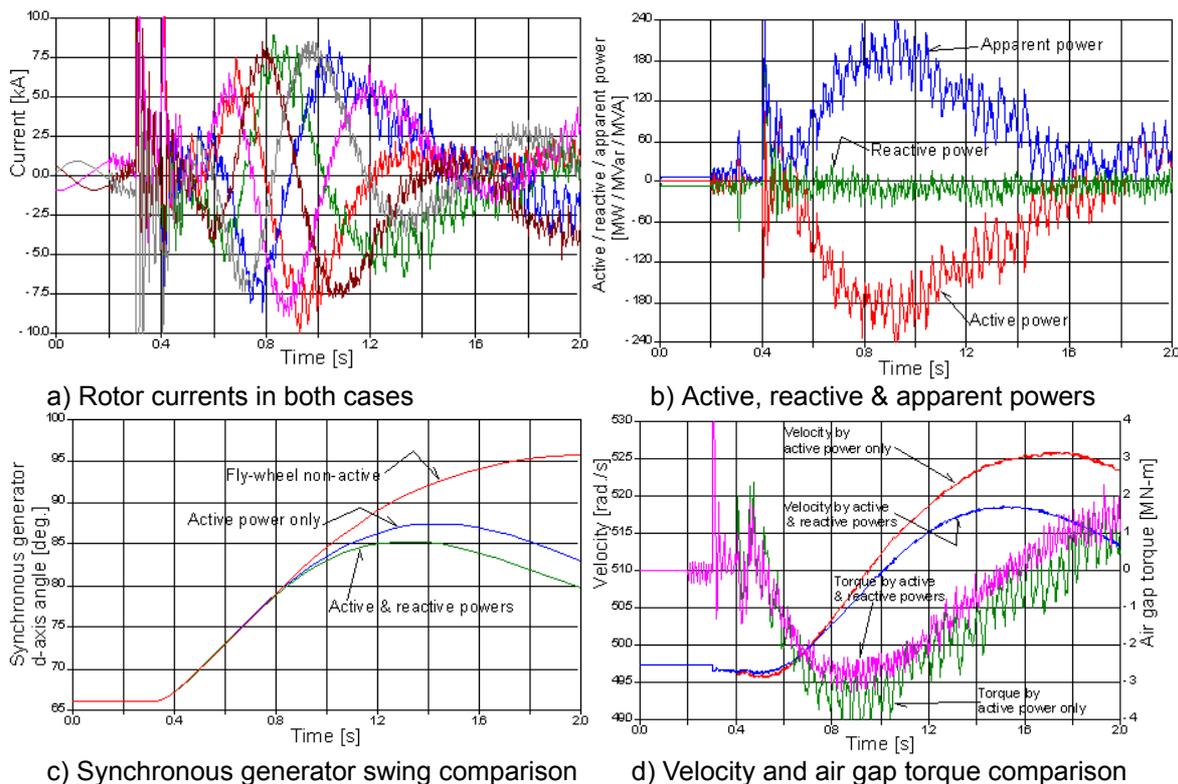
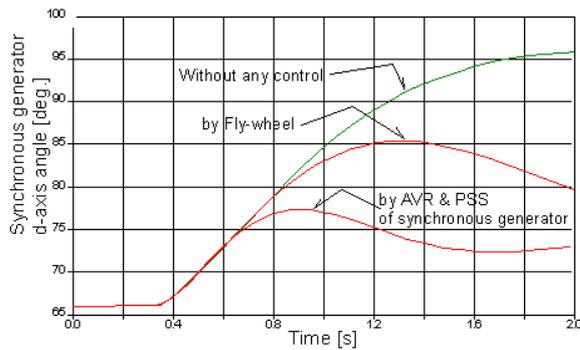


Fig. 10.20 Effects by solo-active power and jointing with reactive power

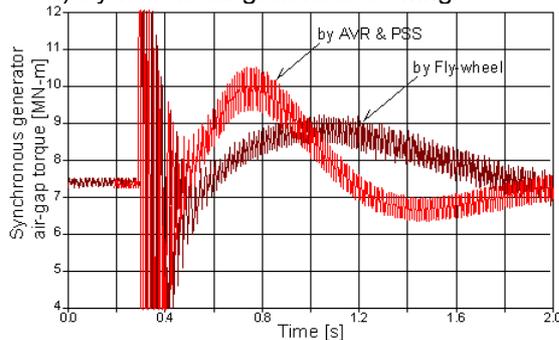
active and reactive powers, the condition is easily introduced. For details, see Dat10-28.dat attached. Comparing to the previous case, some results are shown in Fig. 10.20.

- Rotor currents from the inverter are compared between two cases, where due to approx. equal apparent powers, the maximum crest values are approx. equal by two. On the other hand the phase angle is shifted relevantly. These can be explained by Fig. 8.9, Fig. 8.11 and Appendix 8.1.
- Active, reactive and apparent powers of the fly-wheel are shown. Due to the almost zero reactive

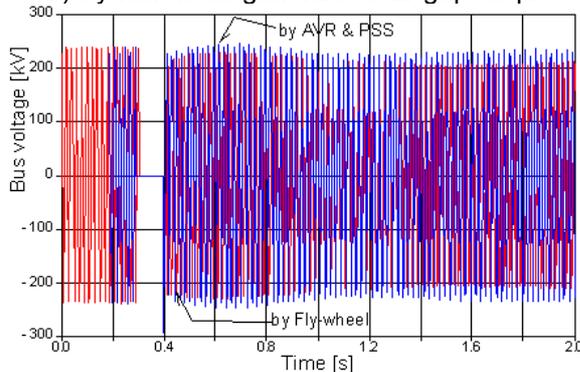
- power, the value of the apparent power is equal to the active one, which is approx. equal to the previous case's apparent one (Fig. 10.19c).
- c) Effects on the synchronous generator's swing (d-axis angle, which is the representative of the transient stability) are compared. In spite of by approx. equal apparent powers, solo-active power control is not so effective compared to by both active and reactive power control. Discussion will be shown later.
- d) By solo-active power, velocity change and air gap torque are higher, though the effect is less.



a) Synchronous generator's swing



b) Synchronous generator's air-gap torque



c) HV bus voltage

Fig. 10.21 Comparison of fly-wheel with AVR / PSS as for transient stability enhancement

$\Delta F$  of the HV bus voltage under "3LG --- 1CCT opening" condition.

- Dat10-27.dat : Active & reactive power output control (of the fly-wheel) case, where the apparent power output is approx. 200MVA (200%) at maximum.
- Dat10-28.dat : Active power only control case, where the output is approx. 200MW at maximum.

### Discussion

In chapter 7, transient stability in the identical one generator vs. infinite bus system is explained. Also significant effect of AVR/PSS to enhance stability is shown. In Fig. 10.21a the effects by fly-wheel generator and AVR/PSS are compared under similar initial load flow conditions. The effect by AVR/PSS is apparently superior. By AVR/PSS the synchronous machine's exciting is controlled, yielding enhancement of the transmission voltage. Therefore, by the increase of the transmission power according to equation 7.1, the air gap torque rises as shown in Fig. 10.21b. The maximum torque is 135% of the initial, and the difference from the initial one, due to the constant mechanical input torque, acts to damp the swing. By the fly-wheel, the maximum torque is 118% which is limited by the fly-wheel rating (over loading included). Moreover, the rise by AVR/PSS is far more quick. As the result, AVR/PSS is more effective in this case.

Nevertheless, depending on the system layout, synchronous generator's and fly-wheel generator's ratings, fault conditions, etc., various results are obtained, with possible superiority in fly-wheel.

### Data file attached

- Dat10-21.dat : One synchronous generator vs. infinite bus system automatically initialised by CAO LOAD FLOW.
- Dat10-22.dat : Manually initialised identically to the above condition.
- Dat10-23.dat : Above system plus fly-wheel generator, the rotor of which is energised by a fixed AC source outside.
- Dat10-24.dat : Ditto, but inverter control program is implemented and checked under the ditto condition. (Inverter non-activated)
- Dat10-25.dat : Current regulated inverter activity is checked energising the fly-wheel rotor to create the same condition as Dat10-23.dat.
- Dat10-26.dat : Total system in Fig. 10.13 is checked where the fly-wheel is controlled by