DESIGN CONSIDERATIONS OF DOL AND VFD JACKING SYSTEM

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ABSTRACT
The jacking system is a key mission critical and safety critical system on a Jack Up platform (JUP). Due to its massive hull, a typical jacking system uses thirty six, fifty four or seventy two motors working in combination to share the load in elevating or lowering the hull against gravity. Distinct characteristics for jacking system loads include high inertia, large variable loads due to different loading conditions of the rig, guide and pinion friction, cyclic loads due to pinion action, and that the system can experience instantaneous load change due to the environment.

In this paper, characteristics and peculiarities to be considered for both DOL and VFD Jacking systems are discussed. Design considerations include start and stop sequences, interaction of the DOL or VFD drive with the braking system, load sharing, system reliability, short circuit current ratings and protection, encoder feedback, shaft voltages, bearing currents, vibrations, cable length and reflected wave phenomena, thermal insulation and inverter duty motors. Owners and rig designers should be aware of the tradeoffs and peculiarities when selecting the type of jacking system to be used in the JUP.

KEY WORDS: Jacking System, Direct-On-Line, Variable Frequency Drives

1. INTRODUCTION

A typical JUP has three truss legs with each leg having three mutually parallel chord members. Each chord member is provided with a pair of opposing rack members which are engaged via pinions to four (refer to Fig. 1), six or eight jacking assemblies with gearbox, motor, and brakes. Due to its massive hull, a typical jacking system uses thirty six, fifty four or seventy two motors working in combination to share the load in elevating or lowering the hull against gravity.

Fig 1: (left) Jacking system with four jacking units per chord (right) Rack and Pinion System

The jacking system is a key mission and safety critical system and is responsible for elevating and lowering the hull in a safe and reliable manner. During jacking, the hull is being displaced vertically. Such loads, also called overhauling loads, invite motion of the load due to the effect of gravity even at zero speed. In elevated condition, if the jacking system malfunctions, loss control and is not able to hold the gravity load, the rig will accelerate and drop downwards into the water until the gravitational forces are balanced by the buoyancy. If the jacking system on one leg malfunctions, that side of the hull will start to descend causing the rig to tilt and the legs to be bent. This hull drop or tilt could cause economic loss or injuries and as a worst case, fatality to onboard personnel.

When designing a jacking system, the characteristic of the load needs to be considered due to the rig structure and the jacking system interaction which can contribute to a large variation in loads in each leg, chord and pinion. There can be significant difference in loading between pinions at each instance. A robust jacking system design will need to consider the effects of these load characteristics for safe and reliable operation.

Long-established Direct-on-Line (DOL) is a simple and robust method to drive the jacking system. The disadvantage of DOL is the high inrush current and the mechanical system has to be designed to withstand the stress and the torque generated. Variable Frequency Drives (VFD) jacking systems claim advantages such as smooth start and stress-reduced jacking due to the ability to control the current, step-less speed control and accurate control of the motor torque and pinion torque. Hence the possibility to optimize the mechanical system. In fact, if the VFD drive system could be designed to be robust and reliable, it could also have the advantage that the hull can be self levelling and also be able to have better control of the RPD of the leg [1]. However, in our investigation, the design and control philosophy is significantly more complex. The system architecture, type of VFD control, brake control, programming and setting of the drives have to be considered to have a safe and reliable system, and does not pose a challenge in the commissioning and operation of the system.

In the following sections, the paper will try to highlight some of the consideration when starting and stopping the jacking system and the interaction with the mechanical brakes, load sharing while jacking and considerations related to system reliability and protection.

2. START, STOP JACKING OPERATION AND MECAHNCIAL BRAKES

2.1. DOL JACKING SYSTEM

When starting the jacking operation, pressing the start jacking button on the jacking console causes the contactors in Fig. 2(a) to be closed. Once the contactors are closed, full line voltages are applied to the motor terminals. To stop jacking, the brakes are sized to stop and hold the hull and the motors are de-energized by opening the main contactors.

2.2. VFD JACKING SYSTEM

As there are many types of VFD controls and configurations available, two sample techniques, with simplified electrical representation, are shown in Fig. 2(b) VFD: Volts per Hertz (V/f) Control with one inverter driving a group of motors and Fig. 2(c) VFD: Vector Control with one inverter driving one motor and individual encoder feedback.

For starting the jacking operation, both V/f and Vector Control are able to offer smooth start by controlling the inrush current through adjusting voltage and frequency input to the motors. In order for the brake to open while generating the necessary torque for the load to maintain at a stationary position, the start sequence has to be parameterized and implemented.

Ref to Fig. 3, using V/f control as an example, pressing the start jacking button on the jacking console will initiate the drive to energize the motor. As the current is a function of voltage and frequency across the motor, a low frequency and voltage can be set initially to prevent the current inrush. By reducing the current, the torque is reduced. This is also known as smooth start.

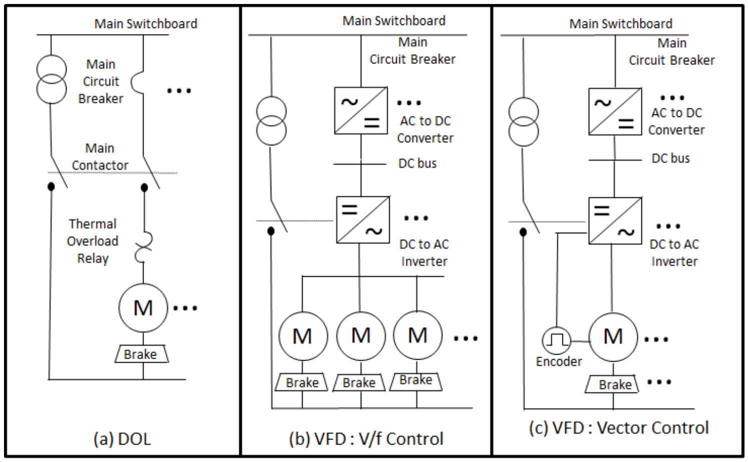


Fig. 2: Simplified electrical representation of (a) DOL, (b) VFD: V/f Control with one inverter driving a group of motors and (c) VFD: Vector Control with one inverter driving one motor and individual encoder

When using a VFD to accelerate a load, the amount of torque and therefore current required to accelerate a load increases as the acceleration time is reduced. The total amount of necessary accelerating torque is the sum of the torque required by the load plus the torque required to overcome the inertia of the rotating assembly [4, 5]. During the release of the brakes, if the stator is not sufficiently energized, there will not be enough current flowing through the stator. Also, if the current is limited, then there is also limited power to overcome the load. In the case when the hull is elevated, at the instance when the brake is released, and if motors have not built up sufficient torque, the motor may not be about to hold the load and the hull may drop.

The start sequence is dependent on several key parameters [2-3] which will need to be tuned, specifically:

i. If the Brake Delay frequency or time is set too low, the brake can be released before the current flowing through the motor generates enough torque to hold the load. On the other hand, if the Brake Delay is set too high, then excessive current at the start may cause a trip.

ii. If the Brake Release Current is too high, the drive will work against the brake and the brake slips at the start.

iii. If the V/f setting is too high, resulting in the torque being too high, the drive will be working against the brake and the brake slips at the start. If the V/f setting is too low, the torque produced in the motor may be insufficient resulting in load drop.

Similarly, the stop sequence is dependent on several key parameters which need to be tuned:

i. If the Slip Prevention Frequency is too high, the drive works against the brakes and the brake slips as the drive is stopping. If the Slip Prevention Frequency is too low, the amount of current flowing through the motor will be insufficient to generate enough torque to hold the load.

ii. If the Slip Prevention Time is too long, the drive works against the brakes and the brake slips as the drive is stopping. If the Slip Prevention Time is too short, the drive is ramped down before the brakes are completely shut which may result in the load dropping.

iii. Similarly, if the V/f setting is too high, resulting in the torque being too high, the drive will be working against the brake and the brake slips at the start. If the V/f setting is too low, the torque produced in the motor may be insufficient, resulting in hull drop.

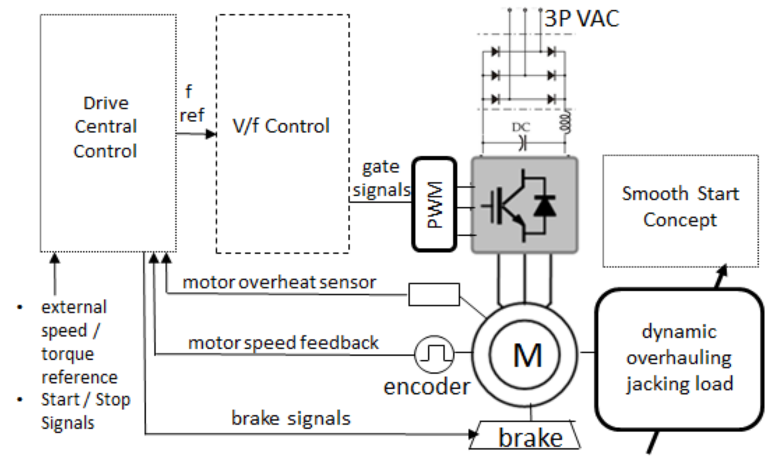


Fig. 3: Simplified representation of V/f control and considerations

2.3. SIMULATION ILLUSTRATION

To illustrate the effects of control parameters on motor starting, a squirrel-cage induction motor controlled by VFD with closed-loop V/f control method is simulated. The effects of motor acceleration time and brake release command trigger time on motor starting process are investigated using a simple single motor single drive system with constant load. From Fig. 4, it is noted the load will drop (negative rotor speed) when the brake release command is triggered. Due to the overhauling type of load the rotor is driven in the opposite direction and the motor is operating in the plugging region. Since the torque is positive but the speed is negative, the plugging torque appears as a braking torque. This illustration is an example to show how suitable parameter settings are critical. If the settings are wrong or can result in the load drop for overhauling loads.

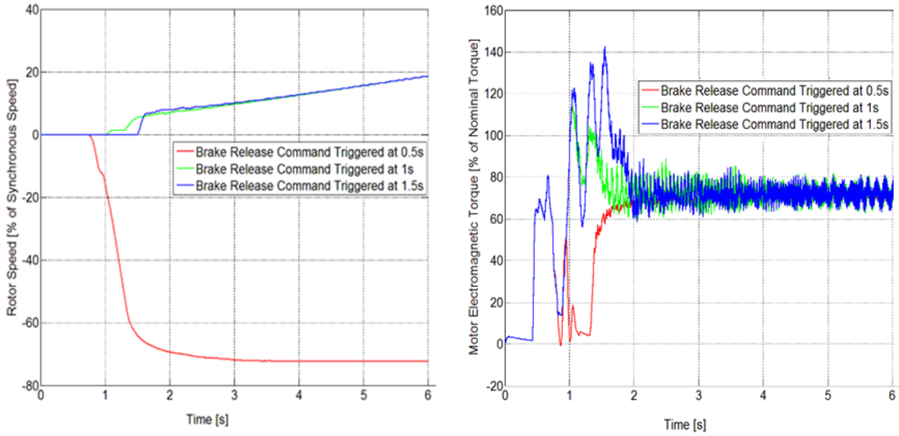


Fig. 4: (left) Motor Speed and (right) torque with Brake Release Command at different timin

REMARK 1

In this section, V/f control is discussed. However, similar consideration applies to vector control schemes. For vector control schemes, accurate tuning of motor parameters is critical as the control method uses the drive internal torque reference. Other parameters for closed-loop vector control include stop timers and torque compensation delay time [2-3].

REMARK 2

In UK HSE report [6], two hoisting incidents were identified attributed to electrical/control system issues. In a 2008 Rotterdam incident, the settings of the sophisticated PLC/inverter motor drive system were found to be at fault. An instance of a similar problem in the U.K. occurred in 2008. In this case it was the hoist motor drive settings at fault and the crane could drop a lifted load without warning. The two incidents are for cranes and similar to the jacking system whereby a load is lifted against gravity. It was report that this scenario has the potential for becoming more prominent as newer systems having ever more sophisticated control systems come on the market and enter service. Much depends on the training/competence of individuals setting up this type of control system and replacement of spare parts once in service to ensure that the internal settings of all motor drives are correct for the application. The settings required to properly control a motor may well differ from the driver manufacturer's default settings and so adjustment during initial erection/commissioning and/or spare part replacement exercises may well be required.

3. JACKING AND LOAD SHARING

As the motors are mechanically coupled through the racks and pinions, each motor must contribute its proportional share of power to the driven load. Load sharing using DOL and VFD, i.e. droop control, torque follower, and speed trim [7-9] will be discussed.

3.1. DOL PASSIVE LOAD SHARING

For speed regulation and load sharing, the DOL system is passive as it depends on the natural characteristics of the motor and the designed slip to regulate the torque and speed

3.2. VFD WITH DROOP CONTROL

Droop Control load sharing operates similar to DOL. All drives use a common speed reference as shown in Fig. 5(a). A droop can be program into the drives to allow the higher loaded motor to slip. If all drives are set to droop, then all drives may share load by reducing speed. This could prevent the system from operating with a rigid speed regulator and may result in poor speed regulation. In a master and follower configuration, if the master drive is not allowed to droop, all follower drives will be "pulled" by the master [9].

3.3. VFD WITH TORQUE FOLLOWER / SPEED TRIM FOLLOWER

From Fig. 5(b), the master drive is operated in speed control mode. The follower drives are operated in torque control mode. In speed trim follower configuration as shown in Fig. 5(c) and 5(d), the master drive is operated in speed control. The follower drives are operated in speed control mode with a speed trim using the torque reference.

The master and follower drives will have to be selected. The consideration is that the torque reference to the follower drives need to consider the effects of variation in load between pairs of pinions, pinions along a chord, and also between legs, the phase difference due to the mechanical offset and also instantaneous load change. For the follower motors, due to variation in loads between pinions, if the load decreases, the torque reference can causes the motor speed to increase rapidly. The design also has to consider the interaction of the load sharing algorithm with the start and stop phases of release and engagement of the mechanical brake. For example, when starting jacking, at zero speed, the master drive torque could be low due to the uneven distribution of loads, as such, the torque reference set point sent to other drives could be insufficient to hold the load while the brakes are released.

For the speed trim, filtering may be required to soften the reaction of the trim regulator. However, if the filter is not properly tuned, the output signal will rapidly and continuously move between the plus and minus limits causing instability [9].

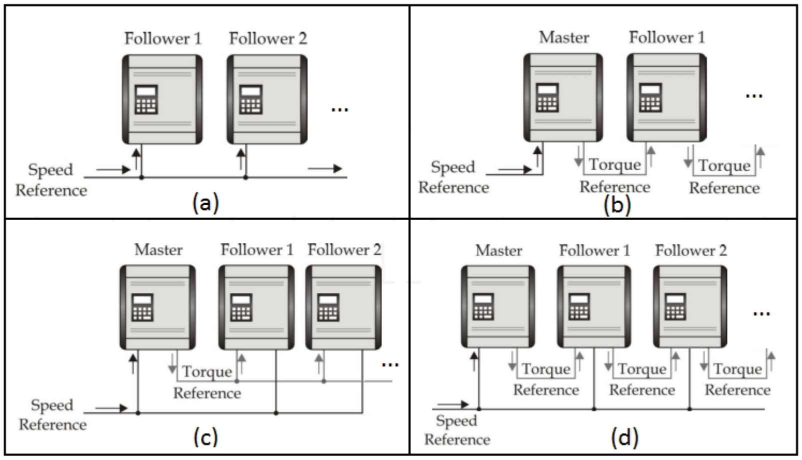


Fig. 5 (a) Speed reference with droop, (b) torque follower, (c) and (d) speed trim follower.

4. SYSTEM RELIABILITY AND PROTECTION

4.1. SYSTEM RELIABILITY

Referring to Fig. 2, for the DOL system, the protection is simple with the main circuit breaker, main contactor and the thermal overload relay. With the addition of more components into the critical path for the VFD jacking system, such as the AC to DC converter, the DC Bus, DC to AC inverter and the encoder, the system reliability is expected to decrease. The mean time to failure (MTTF) for each component will have to be considered and the reliability and availability of the system has to be assessed.

4.2. SHORT CIRCUIT CURRENT RATINGS AND PROTECTION

For VFD, It is estimated in [10] that about 38% of the faults in inverter systems are due to failures of power semiconductor devices such as the insulated gate bipolar transistor (IGBT), which is mostly used in the inverter. Its failures can be broadly categorized as short-circuit and open circuit faults in the power devices. Open circuit faults occurs mainly due to the lifting of a bonding wire caused by thermal stress or by an extremely high collector current and does not cause serious damages. On the other hand, the short circuit failure in the power devices can be catastrophic because the failure propagation to the complementary power device of same inverter pole occurs in less than 10 µs.

Short-circuit current ratings (SCCRs) for VFD is a topic that has been discussed often without clarity [11]. Some manufacturers provide SCCRs based on testing only the output section of VFDs. While this method of test may be suitable for DOL starters used for motor control, the strictest interpretation of applicable standards conducts SCCR tests based on the most likely failure points in the VFD, which is not the output section. Also, due to the electronic nature of VFDs, their characteristics may change depending on their electrical power system connection. The level of prospective short-circuit current (PSCC) available at the point where a VFD is connected to electrical power can have a significant impact on the safety, longevity, and cost of a VFD installation.

Also important is the impact of aging and power supply harmonics on the DC bus capacitors. As evidenced in the catastrophic capacitor failure in cruise ship RMS QM2 [12], the long term degradation and eventual failure of the VFD may lead to shut down of surrounding switchboards. Accessibility to the health status DC link capacitors are important mitigation steps in the failure analysis of the VFD.

4.3. ENCODER FEEDBACK

Within a single-encoder system, the possible fault include (i) a single electrical fault in the encoder, and (ii) a break of the encoder shaft (or loose encoder shaft coupling), or a loose encoder housing which will cause a static state of the encoder signals (that is, they no longer follow a movement while still returning a correct level), and prevent fault detection while the drive is in stop state.

As the drive is likely to be operated under closed loop control, the risk analysis of the machine manufacturer must include all of the faults described above. Additional safety measures have to be taken at suspended/vertical drives or for handling overhauling loads in order to exclude faults [13]. In a jacking system, which uses thirty six and up to seventy two or more motors, inverters and encoders operating in unison but with each inverter operating on individual encoder speed feedback, an incorrect signal fed back from one encoder to one drive may result in that drive motor operating in a “tug of war” with other motors and drives. If a two-encoder system per motor is implemented, the encoders may not be mounted on the same shaft. The algorithm for decision making and response needs to be considered in the case where the two encoders return different values.

4.4. SHAFT VOLTAGES AND BEARING CURRENTS

In many VFD driven motors, shaft currents have been found to discharge through the bearings, breaking down the bearing grease and causing a severe wear pattern in the bearing called "fluting." If allowed to continue, these shaft currents will lead to high motor vibration levels and eventual bearing failure [4, 5].

4.5. VIBRATIONS

Due to the complexity of the mechanical system, the regulators within the VFD controlling speed over a range, flux or current generated could interact with torsional oscillations and cause amplification. The motor and mechanical system may possess several natural frequencies that may be excited by the control when operating within a particular frequency range [4]. These natural frequencies may exist in the horizontal, vertical, axial, or torsional directions and are affected by factors such as the mass and stiffness of the motor base, the type of control, the natural frequencies on the mechanical structure, motor structure, the electromagnetic design of the motor and coupling vibration. A case study in [14] described a multi-motor load sharing system which experiencing severe vibrations at certain speeds and loads. It should be noted that, since mechanical vibration and interaction frequencies are different in every installation, site-specific adjustments of the control software could be required.

4.6. CABLE LENGTH AND REFLECTED WAVE

Location of the MCC where the drives are installed and motors needs to be considered in the design. The cable length needs to be considered due to the reflected wave phenomena which causes voltage overshoots at the motor terminals as shown in Fig. 6(a) [15]. Significant damage to the motor insulation can occur if these overshoots are greater than the maximum rated voltage of the motor [4].

4.7. THERMAL INSULATION AND INVERTER DUTY MOTORS

It should be recognized that motors generate substantial amounts of heat during operation. This heat must be dissipated to maintain cool motor operation and motor longevity. Motor operation at reduced speeds results in reduction of fan cooling effectiveness which can cause the motor to heat excessively and bring about premature motor failure. Applications that require extremely slow (below 6 Hz) or extremely high speeds may require a custom motor design [4]. Harmonics due to short rise times of the synthesized waveforms add to motor heat dissipation requirements. Short rise times can also cause high voltage spikes that can damage the motor insulation.

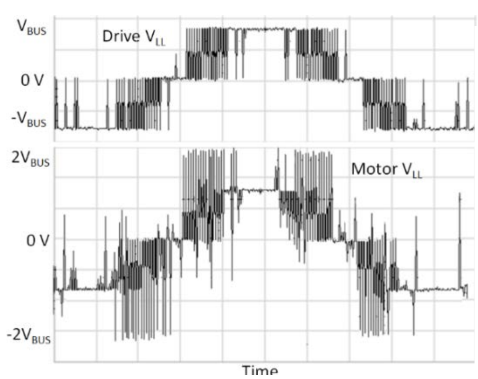
The motor's insulation system is what makes a motor capable of operating with an inverter power supply. For VFD, motor manufacturers have long recognized that 3-phase ac squirrel-cage induction motors that are fed by PWM inverters experience higher dielectric stresses than do equivalent line-fed motors. The fast switching transistors used in modern PWM inverters have helped to produce more sinusoidal currents as well as more efficient and compact inverters. The fast transitions (both turn-on and turn-off) of the transistors helped to enable these improvements but also create higher stresses in the motor insulation. These higher stresses are seen phase to phase, phase to ground, and turn to turn.

Fig. 6(b) shows that a motor, at rated frequency and load, under inverter operation may have a 10°C higher temperature rise than the same motor on sinewave power [14, 16]. Constant Torque (CT) type loads further increase motor temperature rise in Fig. 6(b) as drive output frequency, and thus motor speed, is reduced. This is due to reduced motor cooling since the internal motor fan speed is also reduced. At some frequency an external fan is required for CT loads. Variable Torque (VT) rated loads usually have maximum temperature rise at rated load and frequency.

The failure mechanism associated with these higher stresses is primarily related to partial discharge (PD) activity, also known as corona inception. This is a type of localized emission resulting from transient gaseous ionization in an insulation system when the voltage stress exceeds a critical value. The damage is a cumulative process, much like fatigue failures on a mechanical component.

5. EXTRA TORQUE

The advantage of DOL systems is that is it able to provide extra torque, for example, during leg pulling, i.e. 200-400% of the full load torque for short intervals. The mechanical system is also sized for the extra torque. If programmed in advance, VFD drives are able to provide 150%-200% of the torque for less than one minute. However, the mechanical system of the VFD jacking system also needs to be designed to cater to the torque if required.



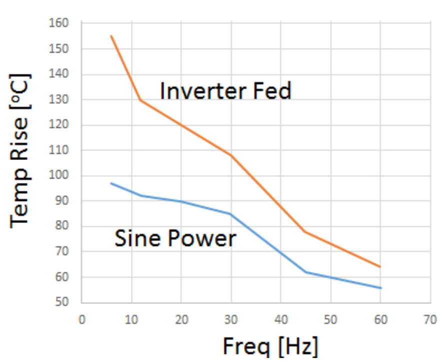


Fig. 6 (a): PWM Voltage at Drive and Motor Terminals and (b) Motor Temperature Rise on Sine Wave and Inverter Power

6. CONCLUSION

In this paper, characteristics and peculiarities to be considered for both DOL and VFD jacking systems have been discussed. Design considerations include interaction of the DOL or VFD drive with the braking system, start and stop sequences, load sharing, system reliability, short circuit current ratings and protection, encoder feedback, shaft voltages, bearing currents, vibrations, cable length and reflected wave phenomena, thermal insulation and inverter duty motors.

The DOL jacking system is a simple and robust system. The key design consideration of the DOL system is on the mechanical system to cater for the high current inrush and the starting torque. The DOL system is mechanically oversized. For VFD jacking system, there can be advantages such as smooth start, step-less speed control and optimization in the mechanical system. The tradeoff is in the increase in complexity, including the system architecture, type of VFD control philosophy, programming and setting of the drive parameters. Other complexities such as system reliability due to an increase of components in the critical path, vibrations due to operation over a speed range, thermal insulation, cable lengths, commissioning, testing and maintenance have to be considered. The design considerations need to be addressed to further enhance jacking system robustness and safety.

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