

ABSTRACT

Fault-tolerant humanoid joint actuators must retain enough motion capability after electrical failures while meeting strict limits on size, weight, power use, and thermal capacity. Conventional three-phase drives are compact and well established. However, their limited electrical redundancy restricts operation after phase or winding faults. Multiphase AC drives add stator phases and electrical degrees of freedom. These allow current redistribution among healthy phases after selected faults. By adding redundancy within the machine, this approach can improve post-fault capability without relying entirely on extra converter hardware. However, it also requires more inverter channels and sensors, complex control, and careful thermal design. This work explains the engineering principles of multiphase fault-tolerant drives for humanoid joint actuators. It examines fault coverage, post-fault capability, current redistribution, and the balance between electrical redundancy and the demands of actuator integration.

1 Introduction

Humanoid robots need joint actuators with high torque density, compact packaging, dynamic response, and reliable operation under demanding mechanical conditions. Unlike fixed-base industrial robots, humanoid robots have a floating mechanical base. Their joint actuator capability therefore directly affects balance, feasible motion, and recovery from external disturbances. In this context, continued motor rotation alone does not establish fault tolerance. The actuator must retain enough torque, speed capability, and thermal margin to support the required robot function.

Conventional three-phase permanent-magnet drives remain the main architecture for electric actuators. They use mature control methods, compact inverters, and established manufacturing processes. However, they provide limited electrical redundancy. If a phase, winding channel, or converter path becomes unavailable, the remaining electrical degrees of freedom may be insufficient to maintain the original actuator capability without further fault-tolerant measures.

Increasing the number of stator phases adds redundancy directly to the electrical machine. Compared with three-phase machines, multiphase machines provide more independent current channels. These allow the controller to redistribute current among healthy phases after selected electrical faults. As a result, the drive can cover more fault cases and support degraded operation after failures that might otherwise cause complete actuator loss [1]–[3].

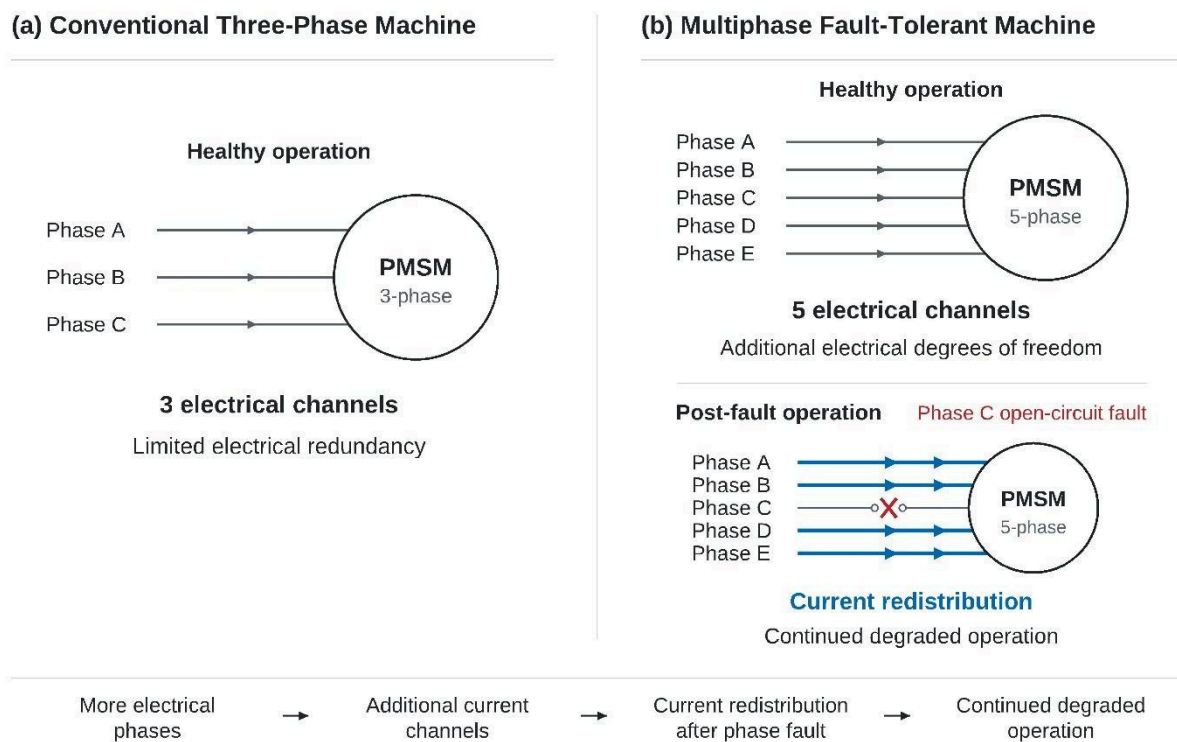


Fig. 1. **Multiphase electrical redundancy concept for fault-tolerant joint drives.** Increasing the number of machine phases introduces additional current channels that enable current redistribution after selected phase faults while increasing converter and control complexity.

This approach differs from the converter-level architectures discussed in [4]. Converter-level solutions add power-electronic paths, such as auxiliary switches or spare inverter legs. In contrast, multiphase drives add redundancy within the

machine itself. As Fig. 1 shows, the extra phases provide electrical channels that can continue to produce torque after a fault.

However, adding phases does not address every fault. It increases inverter complexity, sensor requirements, wiring, control demands, and thermal constraints. Multiphase fault tolerance must be assessed against the full actuator requirements. These include fault type, post-fault capability, isolation capability, size, weight, and power (SWaP) limits.

This work examines multiphase drives for fault-tolerant humanoid joints. It focuses on the trade-offs between electrical redundancy, post-fault actuator capability, and implementation complexity.

2 Electrical Redundancy in Multiphase Machines

The main benefit of multiphase machines is the extra electrical degrees of freedom available after a fault. In a three-phase machine, each phase makes a major contribution to the rotating magnetic field. Losing one phase can therefore severely disrupt torque production. In contrast, a multiphase machine has additional phase channels that the controller can use to compensate for the lost phase.

These additional channels allow the controller to change the phase current references and redistribute torque-producing current among healthy phases. As a result, the actuator may continue operating at reduced capability instead of shutting down immediately.

However, adding conductors alone does not ensure fault tolerance. The resulting capability depends on the interaction between:

- phase number,
- winding arrangement,
- electromagnetic coupling,
- converter capability,
- control strategy,
- current and thermal limits.

Reviews of multiphase AC drives identify phase count as a key factor in fault tolerance. More phases provide more options for current redistribution after electrical faults [1], [5], [8].

For humanoid joints, this flexibility matters because degraded operation may be preferable to complete actuator loss. For example, reduced torque from a leg actuator may help the robot maintain balance or perform a controlled recovery maneuver.

However, the design should use only the electrical redundancy needed to meet the required post-fault capability. Each extra phase requires inverter hardware and increases actuator complexity. Therefore, maximizing phase count is not the design objective.

3 Fault Coverage and Capability after a Fault

Multiphase drives can maintain controlled operation after selected electrical faults by using healthy phases. A drive may still produce its pre-fault torque level at the cost of increased current amplitudes and thermal stress.

Common fault cases include phase open circuits, inverter switch faults, and winding failures. Among these, open-circuit faults are well suited to current redistribution. The faulty phase can often be electrically isolated, while healthy phases continue to produce the required magnetic field.

After a phase open-circuit fault, the controller changes the current references of the healthy phases to compensate for the lost channel. The extra degrees of freedom allow current combinations that are unavailable in conventional three-phase machines. Consequently, the actuator can maintain reduced torque without immediate replacement.

However, the achievable post-fault capability depends on:

- maximum allowable phase current,
- inverter semiconductor current rating,
- winding temperature limits,
- magnetic saturation,

Therefore, continued rotation after phase loss is insufficient to classify a drive as fault tolerant. The remaining actuator capability must meet the required operating conditions. This distinction is especially important for humanoid joints. During dynamic motion, a joint may need high peak torque to recover balance, accelerate, or respond to impact. An actuator that rotates at low speed or lacks sufficient torque may fail to meet these needs.

Accordingly, post-fault capability should be assessed using the related limits on healthy-phase current stress, temperature, and operating duration. These factors must be evaluated together, rather than reduced to a single fault-tolerance measure.

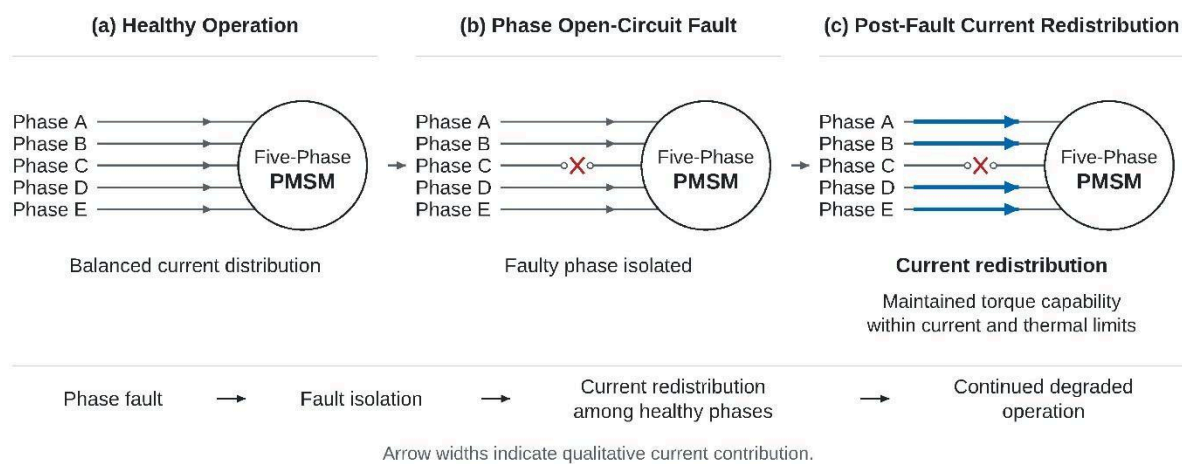


Fig. 2. **Current redistribution principle after a phase open-circuit fault in a multiphase drive.** Following isolation of the faulty phase, the healthy phases increase their current contribution to maintain torque production while operating within current and thermal constraints.

4 Open Circuit and Short Circuit Fault Tolerance

Multiphase architectures offer inherent benefits for open-circuit fault tolerance. However, tolerating an open current path differs from containing a short circuit that remains electrically active.

During an open-circuit fault, the failed phase is removed from the current path. The controller can then use the remaining phases to produce a modified magnetic field and continue generating torque.

In contrast, a short-circuit path remains electrically active. It may cause uncontrolled current, added electromagnetic stress, and excessive heating. In permanent-magnet machines, rotor motion also induces voltage that can contribute to the high current amplitudes through a short-circuit fault.

A multiphase machine may operate well after a phase disconnection yet still need additional measures to limit the effects of a short circuit.

These measures may include:

- electrical isolation between phases,
- increased phase separation (or suitable winding arrangement)
- protection devices,
- fault detection and rapid isolation

Accordingly, the design must keep faults within their intended fault domain, as well as provide sufficient electrical redundancy [8], [9].

For humanoid joints, thermal damage or fault spread within one actuator can reduce the reliability of the whole system. And it is important to prevent a local electrical failure from causing a system failure.

5 Control Requirements and Current Redistribution

Operation after a phase fault depends on both machine redundancy and suitable current references. Extra phases provide more current combinations. However, the controller must be able to use the remaining post-fault combinations effectively [5], [6].

During healthy operation, the controller distributes current across all phases to produce the required torque-generating magnetic field. After detecting and isolating a faulty phase, it must reconfigure the current references for the remaining configuration. The aim is to maintain the required torque within the current and thermal limits of the healthy phases.

Accordingly, post-fault control can be expressed as the constrained optimization problem in (1):

$$J(i_1, i_2, \dots, i_n) \quad (1)$$

Subject to:

$$T_e = T_{ref}$$

And:

$$|i_k| \leq I_{max,k}$$

Where:

- T_e is the electromagnetic torque;
- T_{ref} is the required torque reference;
- i_k is the current of each healthy phase;
- $I_{max,k}$ is the allowable current limit for each phase.

The objective may be to minimize:

- copper losses,
- current imbalance,
- torque ripple,
- thermal stress.

Multiphase control generally uses the extra current degrees of freedom to maintain acceptable torque after a fault. Compared with a three-phase machine, the larger current space offers more ways to produce the required torque during degraded operation [2], [5] and [6].

However, even control cannot overcome the physical limits of the actuator. Once healthy phases reach their current or thermal limits, further optimization cannot restore the lost capability. Therefore, control and physical redundancy must be considered together.

For humanoid joints, the required post-fault operating point depends on the task. Walking may require enough torque to maintain balance. In contrast, manipulation may require accurate position control at lower torque. The controller must therefore meet the expected post-fault task requirements, as well as the electrical conditions for continued operation.

6 SWaP and Actuator Integration

Additional phases improve electrical redundancy but also increase the demands on actuator integration. A higher phase count requires more converter channels, current sensors, gate drivers, and control resources. These requirements affect actuator size, weight, and actuator cost [1], [8]. The main hardware effects are described in the following chapters.

6.1 Power Converter Requirements

Each extra phase needs an extra inverter channel. Increasing phase count increases:

- semiconductor device count,
- gate-driver complexity,
- switching losses,
- cooling requirements.

These added requirements can be substantial because the converter hardware must support the fault-tolerant capability of the machine.

6.2 Electrical Connections and Packaging

Multiphase machines need more:

- winding terminals,
- connectors,
- insulation structures.

These extra interfaces can make mechanical integration difficult because humanoid joints have limited installation space.

6.3 Thermal Management

After a phase fault, healthy phases typically carry more current to compensate for the lost channel. This increases copper losses, winding temperature, and semiconductor stress. Therefore, thermal design must account for both healthy and degraded operation. And a design that provides high post-fault torque but soon exceeds its thermal limits is not a practical fault-tolerant solution [8], [9].

6.4 Reliability and Independence of Fault Domains

More phases do not automatically improve system reliability. Extra components add possible failure points, and several phases may still depend on shared resources [8], [9] including DC bus, cooling path, control electronics, and mechanical structure.

Therefore, the independence of fault domains must be assessed when evaluating a multiphase architecture.

7 Comparison with Converter Level Fault Tolerance

Multiphase and converter-level architectures pursue the same actuator objective but place redundancy in different parts of the drive. Converter-level solutions retain a conventional three-phase machine and add power-electronic paths. In contrast, multiphase solutions add electrical degrees of freedom within the machine. Accordingly, these architectures differ in fault-tolerance mechanisms, post-fault capability, and hardware requirements. Table 1 summarizes their main design differences.

Table 1
Engineering Comparison of Converter-Level and Multiphase Fault-Tolerant Architectures

Architecture	Redundancy Location	Main Fault-Tolerance Mechanism	Main Design Penalty
Switch-redundant converter	Power converter	Fault isolation and electrical reconfiguration	Additional switches and protection circuits
Spare-leg converter	Power converter	Replacement of failed inverter leg	Additional inverter hardware and transfer/isolation circuitry
Four-leg inverter	Power converter	Additional controlled neutral-current path	Additional converter leg and associated current stress
Multiphase machine	Electric machine	Current redistribution among healthy phases	Additional phases, converter channels, sensing, and control complexity

The choice depends on the main constraints of the humanoid joint design. Converter-level redundancy may be more suitable when changing the motor is undesirable. If greater electrical redundancy and phase-fault tolerance are needed, a multiphase machine provides an integrated approach within the machine.

In some systems, both approaches may be needed. For example, a multiphase machine can provide phase redundancy, while converter-level measures add protection and reconfiguration capability.

8 Design Guidelines for Humanoid Joint Drives

The following principles guide the design of multiphase fault-tolerant humanoid joint drives.

1. Define the target faults

The architecture depends on the faults it must tolerate. A design for phase open-circuit tolerance may differ substantially from one that must contain short circuits.

2. Assess the remaining actuator capability

The number of healthy phases does not directly determine actuator capability. Therefore, the assessment must include remaining torque, speed range, current stress, and thermal margins.

3. Use sufficient redundancy

Extra phases improve electrical flexibility but increase inverter size, actuator mass, losses, and control complexity. Accordingly, the preferred design uses the least redundancy that meets the post-fault requirements.

9 Conclusion

Multiphase drives can improve the fault tolerance capability of humanoid joint actuators by adding electrical redundancy within the machine. Extra phases allow greater current redistribution and continued operation after selected electrical faults.

However, multiphase operation does not ensure complete fault tolerance. Open-circuit tolerance and short-circuit containment need different design measures. In addition, current ratings, thermal limits, and integration requirements restrict post-fault capability.

Therefore, phase count and drive architecture should be selected through a system-level assessment of fault coverage, post-fault capability, SWaP limits, and reliability requirements. Multiphase drives form part of a wider actuator fault-tolerance strategy. Within this strategy, machine redundancy, converter architecture, fault isolation, and control reconfiguration must work together to support reliable robot motion.

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