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COPPER-SHEATHED MINERAL-INSULATED CABLE IN VARIABLE FREQUENCY DRIVE APPLICATIONS: ELECTRICAL SURVIVABILITY, EMI CONTAINMENT, AND PRACTICAL ENGINEERING LIMITS

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Abstract—**Pulse-width-modulated variable frequency drives place the motor cable inside the electrical behavior of the drive system. Reflected-wave voltage, common-mode current, cable charging current, electromagnetic interference, and termination quality can all influence whether the installation behaves reliably.**

Most published VFD cable discussion has focused on polymeric shielded tray cable, conductors in conduit, and continuously sheathed mineral-insulated (MI) cable is rarely treated in that discussion, although its construction is materially different: solid conductors, compacted magnesium oxide insulation, and a seamless copper sheath.

Copper-sheathed MI cable should not be treated as a general substitute for established VFD cable constructions. Its strongest case is narrower: fixed motor circuits where environmental survivability is a design requirement and where measured PWM electrical behavior does not introduce unacceptable reflected wave, capacitance, or common-mode current penalties. The sheath may provide a useful concentric high-frequency return path, but that claim depends on measured sheath impedance, termination geometry, bonding practice, and installed workmanship. It is not proven by copper conductivity alone.

This paper develops an engineering assessment framework for multicore copper-sheathed MI cable on PWM VFD outputs. The focus is not promotion of MI cable as a universal VFD wiring method. The focus is the unresolved technical question: where, if anywhere, do the survivability attributes of MI cable justify formal VFD qualification testing? The conclusion is deliberately narrow. MI cable merits evaluation for fixed, harsh-environment, high-consequence motor circuits, but its VFD-specific electrical performance must be established by measured capacitance, surge impedance, common-mode return path, sheath-current, reflected- wave, and termination data.

Index Terms—**Variable frequency drives, VFD cable, mineral insulated cable, copper sheath, magnesium oxide insulation, reflected-wave voltage, common-mode current, electromagnetic interference, cable capacitance, surge impedance, sheath bonding, motor bearing currents.**

I. INTRODUCTION

A motor cable on the output of a PWM variable frequency drive is not doing ordinary feeder duty. It is carrying a switched waveform with steep voltage edges, high-frequency content, and a ground reference behavior that differs materially from conventional 50-Hz or 60-Hz service.

The cable is no longer only a current-carrying link between two pieces of equipment. It becomes part of the drive-motor system itself.

That point has been understood in the VFD literature for years, but it is still too often flattened into rules of thumb.

Bartolucci and Finke identified reflected voltage, bearing-current concerns, and electromagnetic-interference (EMI) con-welded corrugated aluminum-sheathed Type MC cable. Copper-tainment as central to motor-cable selection for PWM AC drives [1]. Bulington, Abney, and Skibinski compared armored cable, conductors in conduit, and shielded tray cable while emphasizing dielectric life, common-mode current, radiated and conducted emissions, and termination practice [2]. Their common message is direct: cable construction matters because the drive output is electrically unforgiving.

The cable industry responded along predictable lines. Dedicated VFD cable designs developed around robust polymeric insulation systems, shields, drain conductors, symmetrical grounding arrangements, and more deliberate

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termination practices. Continuously welded aluminum-sheathed Type MC cable also earned a place in the discussion because its metallic enclosure can provide a low-impedance return path and meaningful EMI containment when correctly terminated[1].

Copper-sheathed mineral-insulated cable has largely remained outside that body of discussion. That omission should not be treated as proof of unsuitability. MI cable is not a minor variation of shielded tray cable. It is a different construction: solid conductors packed in magnesium oxide and enclosed by a seamless copper sheath. Maurer's 1956 heavy-industry paper presented MI cable as a rugged, self-contained system intended for conditions where ordinary wiring methods were not always satisfactory [8]. The Electric Cables Handbook documents the same broad technical identity in more formal cable-design terms [6], [7].

A scope boundary is necessary at the outset. The grounding-symmetry argument developed here applies primarily to multicore copper-sheathed MI cable. The evaluation is strongest for multicore MI constructions in which the seamless sheath encloses the complete phase set. It should not be extended casually to three separate single-core MI cables; that arrangement changes the sheath-current, bonding, induced-voltage, and symmetry problem. The BICC handbook notes that larger MI conductor sizes are commonly supplied as single-core constructions, which is not a small limitation for industrial motor feeders [6].

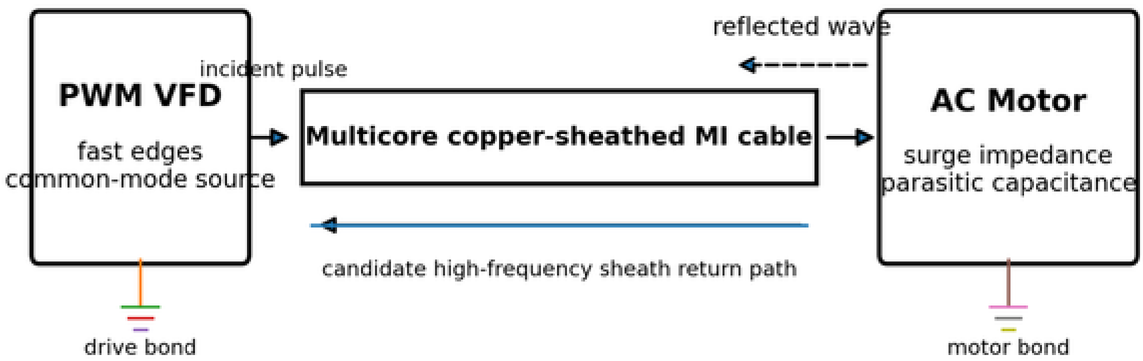

Fig. 1: Simplified PWM VFD-cable-motor system showing incident pulse behavior, reflected-wave concern, and the proposed sheath-based high-frequency return-path question.

The question is not whether MI cable is durable. That case is well established. The real question is whether some features that make it useful in severe industrial environments also make it technically useful, or at least technically acceptable, on the output of a PWM drive. Can a seamless copper sheath help contain high-frequency noise or provide a controlled return path?

Does the compact MI geometry help or hurt reflected-wave behavior?

Does the sheath remain useful after real terminations, cabinet bonds, and installation variation are included?

Those are measurement questions, not catalogue claims.

II. PWM VFD OUTPUT STRESS AND WHY CABLE CONSTRUCTION MATTERS

A PWM inverter controls motor speed by synthesizing a variable-frequency, variable-voltage output from rapid switching of semiconductor devices. The output is not a clean sinusoid. It is a sequence of high-slope voltage transitions. With sufficiently fast rise time and sufficient cable length, the cable behaves less like a lumped feeder and more like a transmission line. Earlier VFD cable literature identified rise times in the approximate range of tens to hundreds of nano seconds as enough to create severere reflected-wave concerns in practical motor circuits [1], [2], [16], [17].

For a 480-V class inverter, the DC bus is well above the line-to-line rmssupply voltage. When a voltage step reaches the motor the terminals and encounters an impedance mismatch between cable and motor, part of the wave reflects. Under severe reflection conditions, terminal voltage may approach approximately twice the incident step magnitude. Some PWM wave magnitude and showed that cable constructions produce conditions can produce more complex transient behavior where repetitive pulses interact before the previous transient has decayed [2], [16], [18].

Two stress categories follow. First, the cable can affect motor stress through reflected-wave overvoltage and fast dv/dt at the line-end turns of the winding. Second, it can affect the wider electrical system through common-mode current, charging current, conducted emissions, and radiated

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EMI. Bearing current damage is often added to the list,but it needs

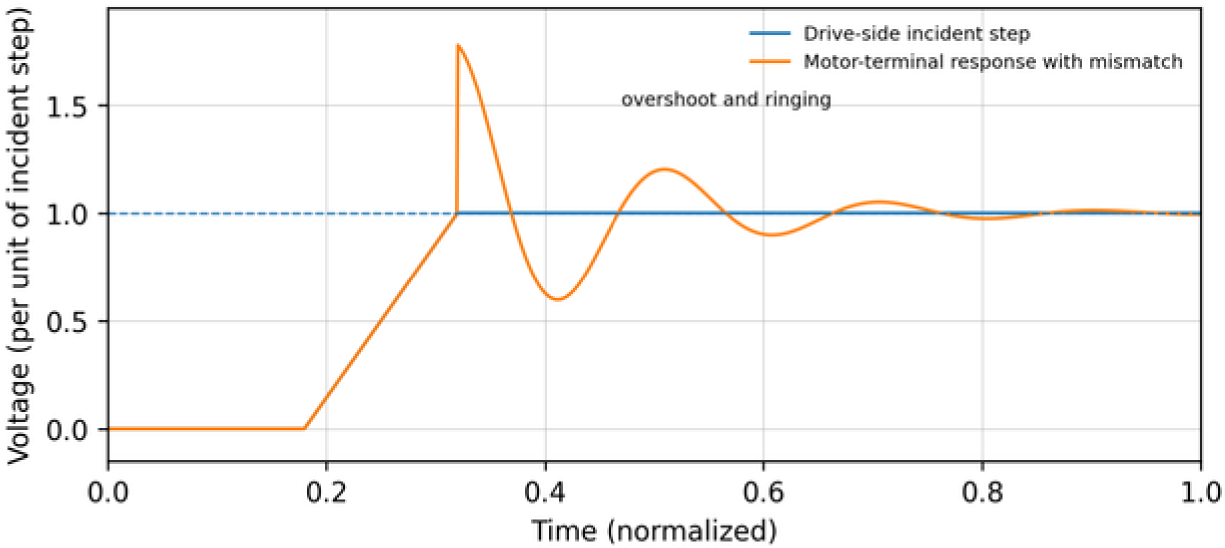

Fig. 2: Conceptual reflected-wave response. A fast incident step can produce motor-terminal overshoot and ringing when cable and motor surge impedances are mismatched.

careful treatment. Cable construction can influence the pathway of common-mode current. It does not remove the source mechanism created by PWM common-mode voltage and the motor's parasitic capacitances.

NEMA MG 1 Part 31 recognizes inverter-fed motor requirements for definite-purpose polyphase machines [3]. IEC TS 60034-25 addresses converter-fed AC machines and their interactions with converter supplies, while IEC TS 61800-8 addresses voltage at the power interface of adjustable-speed drive systems [9], [10]. Those references properly address the drive-machine interface. They do not make cable selection irrelevant. An inverter-duty motor can still be connected through a cable system that creates excessive conducted noise, unacceptable motor-terminal transients, or poorly controlled common-mode return paths.

III. CABLE SYSTEM MECHANISMS RELEVANT TO VFD APPLICATIONS

A. Reflected-Wave Voltage and Motor Terminal Overstress

Reflected-wave behavior is governed by the mismatch between cable characteristic impedance and motor surge impedance. The cable surge impedance is commonly represented as

$$Z_0 = \sqrt{\frac{L}{C}} \qquad (1)$$

where L is distributed inductance per unit length and C is distributed capacitance per unit length. Bartolucci and Finke used this relationship to explain why cable properties affect the inverter-to-motor waveform [1]. Bulington et al. similarly treated surge impedance as a key factor in reflected-wave magnitude and showed that cable constructions produce different impedence behavior. [2], [16], [18]

The voltage reflection coefficient at a discontinuity may be expressed as

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \qquad (2)$$

where Z_L is the effective motor surge impedance. In simplified form, the receiving-end voltage may be represented as

$$V_r = (1+\Gamma)V_{bus}. \qquad (3)$$

A substantial mismatch can therefore produce a motor-terminal voltage materially above the initial inverter step. Cable length also matters. A common critical-length expression is

$$L_c = \frac{vt_r}{2} \qquad (4)$$

where v is wave propagation velocity in the cable and t_r is drive-output rise time [1], [16], [18]. Real PWM behavior can be more complicated than this single-edge approximation, but the expression is useful because it forces the designer to consider lead length and edge rate together.

For MI cable, the reflected-wave question cannot be answered from physical toughness. The compacted magnesium oxide dielectric, the close conductor-to-sheath geometry, and the metallic enclosure may produce capacitance and inductance values that differ substantially from shielded polymeric VFD tray cable and corrugated aluminum-sheathed MC cable. If the resulting shifts farther from motor surge impedance, reflected voltage may worsen. If it shifts favorably, it may help. Without measured values, neither claim is defensible.

B. Common-Mode Current and Ground-Referenced Noise

PWM drives generate common-mode voltage components because the three output phases do not remain at a fixed neutral reference with respect to ground. These rapid common-mode voltage transitions couple through parasitic capacitances in the motor and cable, producing high-frequency current paths to ground. Bulington et al. describe the practical consequence: capacitance from drive output conductors and motor windings to ground becomes a low-impedance path at high frequency unless the cable system provides a preferred return path back to the drive [1], [2], [11], [20].

A simplified expression for charging current is

$$i = C\frac{dv}{dt}. \tag{5}$$

The equation is simple, but the design pressure is real. Higher capacitance and faster voltage edges raise transient current demand. A cable that improves containment through a continuous metallic sheath may also have a different conductor to-sheath capacitance profile. That can affect common-mode current magnitude, charging-current demand, and drive nuisance behavior.

Copper-sheathed MI cable offers a continuous metallic enclosure with high conductivity. In principle, a copper sheath bonded at both the drive and motor ends may provide a controlled return path for portions of the common-mode current. Bartolucci and Finke reached a parallel conclusion for continuously welded corrugated aluminum sheaths: a low- resistance, properly terminated metallic sheath can improve the return path for capacitive currents and enhance EMI containment [1]. Electrical similarity should not be confused with equivalence. A corrugated aluminum sheath surrounding polymeric insulated conductors is not the same as a seamless copper sheath closely surrounding magnesium-oxide-insulated conductors. Conductor geometry, dielectric constant, capacitance, sheath resistance, high-frequency impedance, and termination geometry all have to be measured in the actual construction. Copper conductivity is promising. It is not proof.

C. Bearing Currents: What the Cable Can and Cannot Solve

Bearing-current discussions invite overstatement. PWM drives can excite shaft voltage and bearing discharge mechanisms through capacitive coupling between stator, rotor, frame, and grounding system. Bartolucci and Finke discuss circulating and capacitive bearing-current concerns and note that cable symmetry and grounding return-path design may influence common-mode current behavior [1]. Bulington et al. cite field experience in which motor bearing failures returned after output cable replacement with continuously welded aluminum- armored cable. The lesson is important: cable construction alone should not be treated as a complete bearing-current solution [2]. Numerous studies have linked PWM drives to shaft voltage accumulation and bearing discharge mechanisms [13], [15]. Cable construction may influence the pathway of common-mode current but does not remove the source mechanism [13], [14]

That distinction matters for MI cable. A continuous copper sheath may help control a high-frequency return path. It may reduce radiated noise. It may change common-mode current distribution. It should not be claimed as a stand-alone bearing- current mitigation method without evidence. Shaft grounding rings, insulated bearings, common-mode chokes, filters, drive settings, motor design, and grounding practice remain part of the mitigation strategy.

D. Capacitance, Surge Impedance, and Symmetry

Cable capacitance affects charging current, common-mode current magnitude, drive over current trips in small drives, and characteristic impedance. Bulington et al. showed that capacitance can vary materially across cable designs and that lower capacitance tends to reduce cable charging current under fast PWM switching [2], [17], [18], [19]. They also noted that shields and armor can increase capacitance even while improving EMI control.

The general cable-design relationships are established. The Electric Cables Handbook describes capacitance as a function of geometry and dielectric permittivity and shows that metallic layers and conductor spacing shape electrical behavior [5]. For MI cable, the critical parameters are the magnesium oxide dielectric, conductor to-sheath proximity, conductor spacing, and whether the cable is multicore or assembled from separate single-core cables. A multicore MI cable with the complete phase set inside one sheath is a different problem from three separately sheathed single-core MI cables.

E. EMI Containment and Continuous Return Paths

EMI control in VFD motor circuits depends on loop area, high frequency return paths, and preventing uncontrolled current from using the facility grounding grid as the path of least impedance. The VFD cable literature strongly supports the value of a continuous, well-bonded metallic shield or sheath [1], [2], [11], [20].

IEC 61800-3 provides the broader EMC framework for adjustable speed power drive systems [11].

A seamless copper sheath is attractive from this standpoint. It is not braid with coverage gaps. It is not foil that becomes difficult to terminate consistently in harsh service. It is a metal tube. If properly bonded, that structure may provide strong field containment and a useful common-mode return path. But high frequency performance depends on more than dc resistance. Sheath geometry, skin effect, termination circumference, contact resistance, enclosure bonding, and the path taken after current leaves the sheath all matter. A poorly bonded sheath at the motor box or drive enclosure will not deliver the expected benefit.

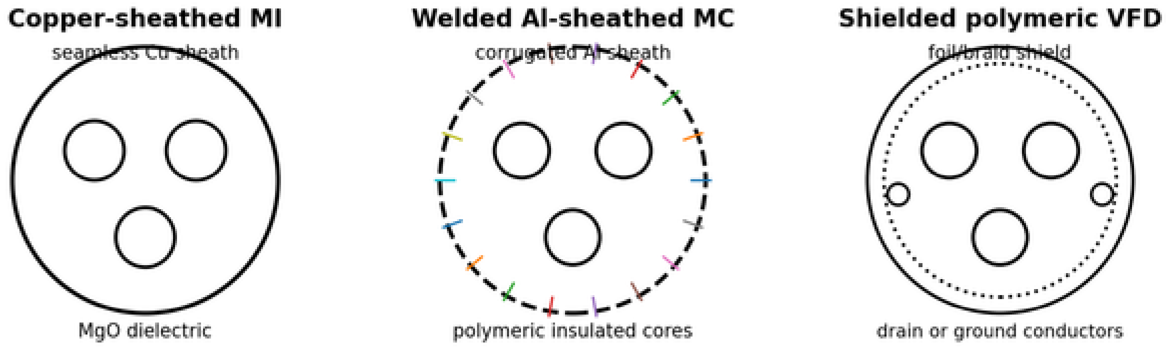

Fig. 3: Conceptual comparison of copper-sheathed MI cable, continuously welded aluminum-sheathed MC cable, and shielded polymeric VFD cable. The geometry is illustrative, not a dimensional product drawing.

IV. COPPER-SHEATHED MI CABLE CONSTRUCTION

A. Solid Conductors and Cable Geometry

Conventional copper-sheathed MI power cable employs solid metallic conductors within compacted magnesium oxide. The cable is manufactured through a reduction process that consolidates the conductors, mineral insulation, and sheath into an integrated structure [6]. In fixed installations this stable geometry can be useful. Conductors do not migrate in a soft filler system, and the cable does not rely on polymeric bedding to retain shape.

That stability has two possible VFD consequences. It may improve repeatability of electrical parameters from cable to cable. It may also result in capacitance values that are higher than some low capacitance VFD cable designs. This is a measurement issue, not a rhetorical one.

B. Magnesium Oxide Insulation

Magnesium oxide is the defining dielectric of MI cable. The BICC handbook describes magnesia as hygroscopic before proper termination but stable after sealing, with high-temperature behavior dependent on grade and impurity control [6]. Unlike organic insulation systems, magnesium oxide does not age through polymer-chain degradation because no polymer chain is present.

That difference matters where cable life is governed by heat, fire exposure, radiation, or chemical and mechanical abuse. It matters less if the dominant problem is reflected-wave stress caused by a poor drive-motor-cable match. The handbook notes that MI cables can operate continuously at elevated temperatures and can continue under severe short-duration thermal exposure, limited ultimately by sheath and termination behavior [7]. Those properties support the survivability argument. They do not prove VFD waveform compatibility.

C. Seamless Copper Sheath as Metallic Containment and Return Path

The copper sheath is central to the MI VFD question. In conventional MI use, the sheath provides environmental containment, mechanical durability, and a conductive protective path where permitted and properly engineered. Maurer presented MI cable as a rugged self-contained metallic system suitable for demanding industrial service [8].

For VFD applications, the sheath may serve three functions: physical barrier, protective conductor path where permitted, and potential high-frequency return path. The third function is the unresolved question. The test question is narrow: does the installed sheath-and-termination system provide a lower and more controlled high-frequency return path than the surrounding grounding network over the frequency range excited by the drive? If not, the copper sheath is only a

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robust enclosure, not a demonstrated VFD return-path advantage.

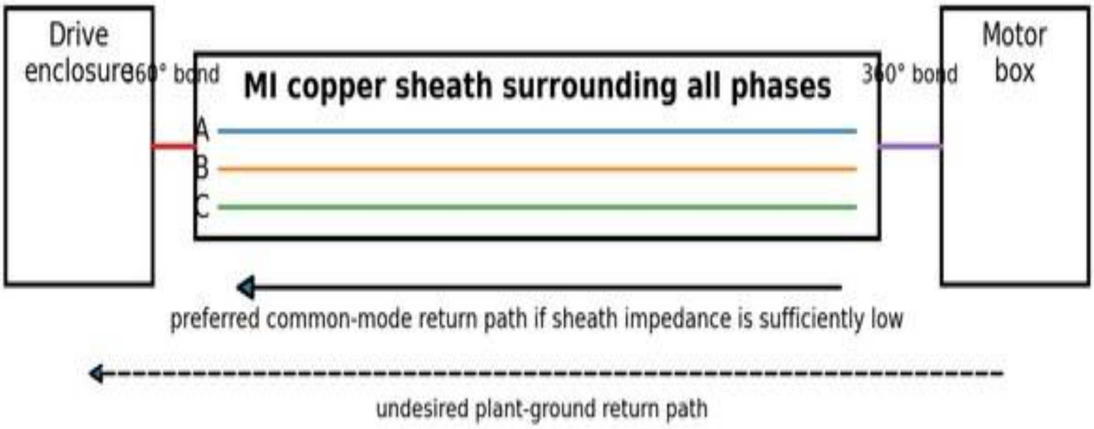

Fig. 4: Conceptual high-frequency return path through a bonded copper sheath.

The useful question is installed sheath-and-termination impedance, not dc continuity alone.

A three-conductor copper-sheathed MI cable does not inherently require segmented grounding conductors to achieve the same geometric purpose as some polymeric VFD cable constructions. Segmented or symmetrically distributed grounds are commonly used in conventional VFD cables to avoid the asymmetry caused by a single off-center equipment grounding conductor. In a multicore MI cable, the seamless sheath already forms a concentric metallic enclosure around the complete phase set. If that sheath is intentionally qualified and used as the protective and high frequency return structure, the primary design question is sheath and termination impedance, not whether segmented grounds should be added by reflex.

If the design abandons reliance on the sheath and substitutes internal grounding conductors, then a single off-center ground would be difficult to defend from a symmetry standpoint. A distributed arrangement might then be more credible. But that would be a different cable architecture requiring its own qualification. Electrical suitability and code or listing acceptance also remain separate questions. A sheath may be electrically attractive and still require confirmation under the applicable product listing, installation method, and governing code.

D. Comparison with Existing VFD Cable Families

Continuously welded aluminum-sheathed MC cable has already been argued in the IEEE literature as a strong VFD cable option cable because of low-resistance sheath return, cable symmetry, and EMI performance when properly grounded [1]. Shielded polymeric VFD tray cable has been developed expressly around drive-system concerns: dielectric with stand, shield coverage, drain conductors, flexibility, and termination convenience [2].

Copper-sheathed MI cable has a different strength profile. It may exceed both alternatives in thermal survivability, fire endurance, radiation tolerance, and resistance to organic insulation aging. It is usually less flexible, more workmanship sensitive at terminations, and less documented as a VFD cable construction. Its argument is therefore application-specific, not universal.

V. POTENTIAL ADVANTAGES IN SELECTED VFD SERVICE

A. Thermal and Environmental Survivability

Where the installation environment dominates the risk picture, MI cable enters the discussion quickly. The BICC handbook documents high-temperature capability, resistance to severe service, and radiation-related advantages compared with organic cable constituents [7]. These properties are relevant to VFD driven loads serving smoke-control fans, emergency ventilation, thermal process equipment, and fixed motor loads in environments hostile to ordinary organic cable materials.

This does not make MI cable electrically superior on a VFD output. It changes the design question. In some installations, the relevant question is not simply which cable has the lowest EMI or lowest capacitance. It is which cable maintains acceptable function after the route has become hostile to ordinary cable materials.

B. Continuous Metallic Sheath and EMI Containment Potential

A seamless copper sheath is electrically attractive. Copper conductivity is high, and a continuous tube has no braid coverage gaps or foil overlap discontinuities. A bonded copper tube surrounding the conductors should, in principle, offer strong field containment and a direct path for some high- frequency current components.

That is a hypothesis worth testing. It should not be presented as a result. High-frequency common-mode behavior depends on the installed path, including the termination and enclosure. Where a motor lead passes near sensitive instrumentation or where the plant grounding grid should not be used casually as a high-frequency return path, a qualified copper-sheathed MI system may prove useful.

C. Resistance to Organic Insulation Aging Mechanisms

Bulington et al. emphasize that repetitive PWM voltage stress can affect cable insulation life and that dielectric selection and thickness matter [2]. MI cable avoids many organic- insulation aging mechanisms because its primary dielectric is inorganic magnesium oxide. It does not avoid moisture vulnerability at failed terminations, high-energy discharge damage, or the need to characterize electrical stress. Still, the failure conversation differs: there is no PVC nylon skin to carbonize, no conventional XLPE water-treeing mechanism, and no organic filler system to embrittle.

VI. TECHNICAL CONCERNS AND ENGINEERINGLIMITS

A. Reflected-Wave Behavior Is Not Automatically Improved

MI cable cannot be called better for reflected-wave behavior without data. Reflected-wave performance depends on cable characteristic impedance relative to motor surge impedance. Since depends on distributed inductance and capacitance, and since MI cable geometry and dielectric properties differ materially from polymeric VFD cable, the direction of the effect cannot be assumed [16, [18].

A copper sheath may reduce radiated emissions and improve return-path control while simultaneously increasing conductor- to sheath capacitance. Increased capacitance could lower surge impedance and worsen mismatch with some motors. Or it may not. The answer depends on measured values.

B. Capacitance and Characteristic Impedance Must Be Quantified

Dedicated VFD cable papers measure and compare capacitance, common-mode behavior, and reflected-wave behavior [1], [2]. MI cable should be held to the same standard. At minimum, phase to-phase capacitance, phase-to-sheath capacitance, distributed inductance, propagation velocity, and characteristic impedance should be measured for the exact multicore MI construction under consideration.

C. Sheath Bonding May Influence Common-Mode Current Paths

Bonding a sheath at both ends can create an intentional return path for high-frequency common-mode current. It can also create sheath-current and loss considerations, especially if the construction changes from multicore to separate single-core cable. The BICC handbook's discussion of sheath losses in single-core cable systems is a reminder that metallic sheath current should be understood, not ignored [1], [5], [11], [20] .

For multicore copper-sheathed MI cable, the sheath is the natural candidate to serve as the concentric protective and high-frequency return structure. A dc continuity test is not enough. Contact resistance, gland geometry, metal-to-metal engagement, bonding surface preparation, and the route from sheath to enclosure all matter.

D. Installation Rigidity, Terminations, and Workmanship

MI cable installation is a skilled activity. Its metallic construction and termination requirements can be advantages in permanent installations but disadvantages where field flexibility is valued. VFD service adds another requirement: the termination must preserve both moisture sealing and high- frequency bonding. A poorly bonded termination can defeat the sheath-containment argument. A poorly sealed termination can compromise insulation resistance.

E. Filters May Still Be Required

Cable selection should not be used to avoid an output filter where the drive-motor combination already requires one. If measured MI cable impedance and motor-terminal waveform data still place the installation in a reflected-wave risk region, a dv/dt filter, sine-wave filter, or other manufacturer-approved mitigation remains part of the design. MI cable may change the survivability argument. It does not repeal transmission-line behavior.

TABLE I: Comparison of Cable Construction Features Relevant to PWM VFD Service

Feature	Copper-sheathed MI cable	Aluminum-sheathed MC cable	Shielded polymeric VFD cable
Primary dielectric	Compacted magnesium oxide	XLPE/EPR or similar organic Dielectric	XLPE or similar organic dielectric
Metallic containment	Seamless copper sheath	Continuously welded corrugated aluminum sheath	Braid/foil shield system
Thermal survivability	Very high, subject to termination and sheath limits	Moderate to high, limited by polymeric materials	Moderate, polymer dependent
Installation flexibility	Lower; best suited to fixed routes	Moderate	Higher
Termination sensitivity	High; sealing and bonding both matter	Moderate to high	Moderate
VFD-specific test maturity	Limited public data	Established literature	Established literature
Potential EMI containment	Promising; requires validation	Strong when properly bonded	Strong when properly terminated
Capacitance concern	Must be measured; sheath geometry may matter	Known and construction dependent	Known and construction dependent
Grounding geometry	Multicore sheath may provide concentric return path	Sheath plus grounds used in published designs	Often uses symmetrical or segmented grounding conductors

VII. APPLICATION SCENARIOS WHERE MI MAY MERIT CONSIDERATION

A. Smoke-Control and Emergency Ventilation Fans

Smoke-control and emergency ventilation fans are probably the clearest first application to examine. These systems can combine a fixed motor location, a cable route that may be exposed to abnormal thermal conditions, and a failure consequence not well represented by ordinary production downtime. Where a VFD is retained for control flexibility, balancing, or commissioning, the cable decision should not be reduced to a conventional industrial VFD-cable default. The question becomes whether a survivable motor-circuit wiring method can be paired with a drive system without creating unexamined PWM-side electrical penalties.

B. Fixed VFD Loads Exposed to Heat, Oil, Mechanical Abuse, or Difficult Replacement

Maurer’s heavy-industry discussion remains useful because, the underlying installation problems have not disappeared: heat, oil, mechanical abuse, difficult routing, and the cost of repeated maintenance in harsh locations [8]. VFD deployment has expanded substantially since that paper was written, but severe industrial environments still reward cable systems that tolerate physical punishment. MI cable belongs in the VFD conversation when that environmental problem is real, not when ruggedness is only an attractive word.

C. Radiation- or Contamination-Sensitive Fixed Installations

The BICC handbook notes that MI cable constituents are comparatively resistant to radiation effects compared with organic insulation systems [7]. That property may be relevant in selected industrial or nuclear-adjacent fixed motor circuits where cable replacement or decontamination is operationally undesirable. This remains a secondary application class in the present argument. It becomes credible only when an actual exposure case exists and the drive-side electrical behavior is evaluated separately.

D. High-Consequence Fixed Motor Circuits

Not every VFD motor feeder deserves an atypical cable solution. Some do. A cable serving a mission-sensitive fixed motor, difficult-to-access process load, or emergency-support function may justify a broader life-cycle assessment than an ordinary convenience-driven cable selection. MI cable is most persuasive where the environment is hostile enough, the load consequential enough, and the installation fixed enough that survivability becomes part of the electrical design decision.

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VIII. ENGINEERING ASSESSMENT METHODOLOGY

A useful assessment method should behave less like a catalogue selection checklist and more like a sequence of engineering screens.

A. Screen 1: Establish the Drive-Motor Stress Envelope

The first screening question is whether the drive-motor pair already requires output mitigation because of cable length, rise time,or motor insulation limits.If it does, MI cable does not remove that requirement. The evaluation should identify drive output voltage, converter topology, switching edge rate where available, carrier strategy, manufacturer motor-lead limits, and motor insulation capability. NEMA MG 1 Part 31, IEC TS 60034-25, and IEC TS 61800-8 provide the relevant motor and interface context [3], [9], [10].

B. Screen 2: Characterize the MI Cable as an Electrical Component

The second question is whether the proposed MI construction has measured capacitance and surge impedance values that keep motor terminal voltage within the intended design envelope. The minimum data set includes phase-to-phase capacitance, phase-to sheath capacitance, distributed inductance, propagation velocity, and characteristic impedance. These values should be measured for the specific construction, not inferred from cable families that use different geometry and dielectric systems. [1], [11].

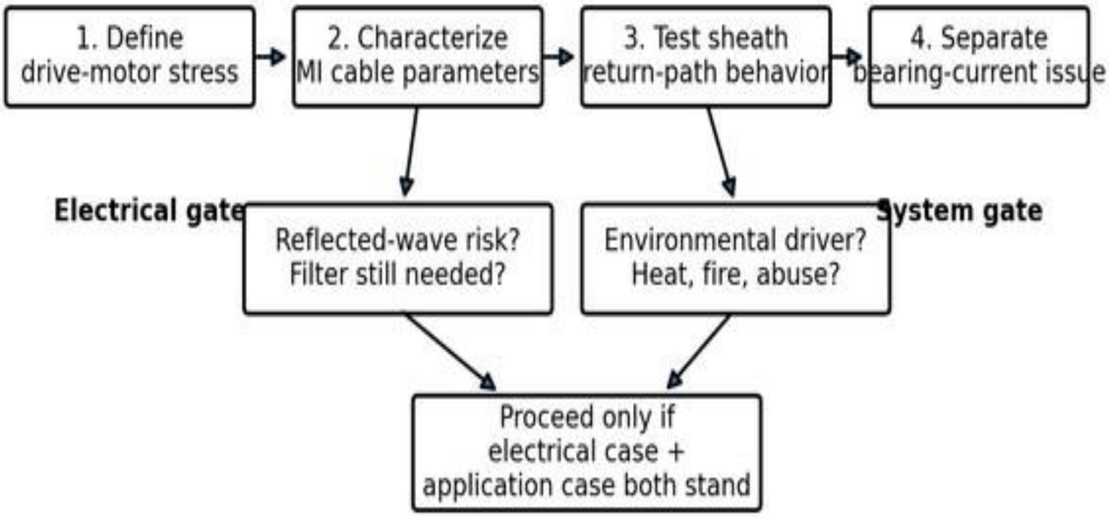

Fig. 5: Decision framework for evaluating copper-sheathed MI cable in VFD service. The environmental justification does not replace electrical qualification.

C. Screen 3: Test the Sheath-Based Return-Path Assumption

For multicore MI cable, the sheath is the natural candidate for the concentric high-frequency return structure. The assessment should determine whether the installed sheath and terminations provide a controlled return path over the frequency range relevant to PWM common-mode current. The study should not presume that segmented internal grounding conductors are required if the sheath is being evaluated as the return structure [16], [17], [18].

D. Screen 4: Treat Bearing-Current Mitigation Separately

The cable may influence current pathways. It does not eliminate the source mechanism created by PWM common-mode voltage. Bearing-current mitigation should therefore be evaluated separately through motor design, shaft grounding, insulated bearings, common-mode chokes, filtering, or other measures appropriate to the drive system [1], [11].

E. Screen 5: Confirm the Application Justification

The environmental driver should be specific: high heat, fire exposure concern, radiation, contamination, mechanical abuse, or replacement difficulty. If none of those are present, a purpose-built polymeric VFD cable or established armored VFD construction may remain the more rational choice [4], [9], [12].

IX. RECOMMENDED TEST PROGRAM

The evidence gap is experimental. Copper-sheathed MI cable should be evaluated against established VFD cable alternatives under controlled and comparable conditions. A defensible program would compare at least three cable families: representative multicore copper-sheathed MI cable, continuously welded aluminum-sheathed MC cable, and a recognized shielded polymeric VFD cable[1],[2].

A. Cable Parameter Characterization
The first phase should establish the electrical fingerprint of the MI construction. Phase-to-phase and phase-to-sheath capacitance should be measured alongside distributed inductance, propagation velocity, and characteristic impedance. Results should be reported directly against comparator cable families, not as isolated MI values.

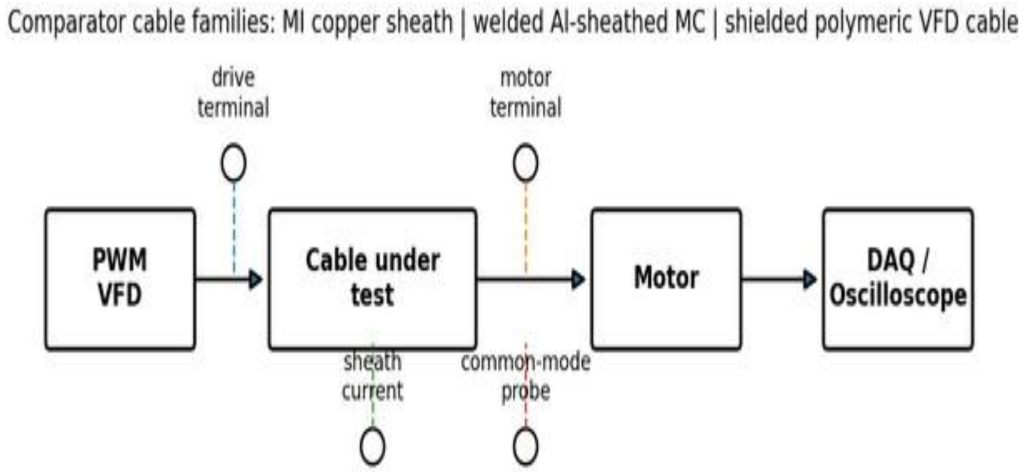

Fig. 6: Proposed comparative test arrangement for MI cable, aluminum-sheathed MC cable, and shielded polymeric VFD cable under equivalent drive, motor, and termination conditions.

B. Reflected-Wave Testing
Motor-terminal voltage should be measured using a controlled PWM drive and a defined set of cable lengths below, near, and beyond estimated critical length. The test matrix should vary switching edge rate where practical and report waveform shape, ringing, peak voltage, and settling behavior. IEC TS 61800-8 is relevant because the test objective is fundamentally a power interface voltage question [10].

C. Common-Mode Return-Path Testing
The return-path claim is the most important electrical hypothesis. Common-mode impedance should be measured over a frequency band selected to capture dominant high-frequency content associated with representative PWM switching edges. The MI sheath should be tested with low-impedance bonding at both ends, and comparator cables should receive equally disciplined terminations. The study should report whether the sheath path remains practically lower than undesirable alternative return paths at the frequencies of interest.

D. Sheath Current and EMI Measurement
Sheath-current measurements should be made during representative PWM operation at multiple operating points. These data should be read together with EMI measurements. A higher sheath current is not automatically bad if it represents successful diversion of common-mode current away from a plant-ground path. It is not automatically good if it reflects excessive displacement current burden created by cable capacitance. IEC 61800-3 provides the broader EMC context [11].

E. Termination and Installation Sensitivity
The MI concept may succeed or fail at the termination. The test program should vary bonding surface preparation, gland type, contact geometry, assembly repeatability, and simulated field contamination. DC continuity should be recorded, but the more important result is whether small installation differences materially alter high-frequency return behavior.

F. Environmental Conditioning
Environmental testing should focus less on re-proving the general reputation of MI cable and more on the specific VFD proposition. Thermal cycling, vibration, and moisture challenge at the termination interface should be followed by repeat electrical measurements. The objective is to determine whether the electrical assumptions made during initial testing remain stable after the cable system has experienced the kind of stress that makes MI cable attractive in the first place.

X. DISCUSSION

The useful way to think about copper-sheathed MI cable in VFD service is not as a replacement for every established VFD cable type. It is a candidate for a narrower and more demanding application class. The case becomes stronger when the circuit is fixed, the environment is severe, and the consequence of cable failure is high. It becomes weaker when installation flexibility, low-cost, and catalog familiarity are the dominant concerns.

TABLE II: Proposed Comparative Test Matrix for Multicore Copper-Sheathed MI Cable in PWM VFD Service

Test area	Core question	Required comparison	Decision value
Cable electrical parameters	What are phase-to-phase capacitance, phase-to-sheath capacitance, inductance, propagation velocity, and characteristic impedance?	MI vs. aluminum-sheathed MC vs. shielded polymeric VFD cable	Establish whether MI starts from a favorable or unfavorable transient profile.
Reflected-wave behavior	What motor-terminal overvoltage occurs as rise time and cable length vary?	Same drive, motor, lengths, and termination discipline	Determine whether MI improves, worsens, or does not materially change terminal stress.
Common-mode return Impedance	Does the bonded copper sheath provide a lower high-frequency return impedance than comparator constructions?	Equivalent terminations for all cable families	Test the central sheath-return hypothesis.
Sheath current and EMI	What current actually flows in the sheath, and what conducted/radiated emissions result?	Bonded sheath or shield configurations under PWM operation	Distinguish useful return-path behavior from excessive displacement-current burden.
Termination robustness	Does bonding remain repeatable across realistic installation variation?	Multiple specimens, controlled assembly differences	Identify whether performance depends on fragile workmanship.
Environmental conditioning	Do thermal cycling, moisture challenge at terminations, and vibration alter electrical behavior?	MI specimens before and after Conditioning	Verify that environmental strength is not lost at the termination interface.
Filter interaction	Does any cable family materially change the need for dv/dt or sine-wave filtering?	No filter vs. approved mitigation	Prevent unsupported claims that cable selection alone solves long-lead or fast-edge problems.

The published VFD cable literature is clear on the mechanisms that matter: reflected-wave voltage depends on cable and motor impedance interaction; common-mode noise depends on high frequency current paths; bearing-current issues are influenced by the whole drive-motor-grounding system; and terminations matter because a shield or sheath that is poorly bonded is not performing the job implied by its material description [1], [2]. None of those lessons disappear when MI cable enters the discussion. However, the absense of published copper-sheath MI cable testing under PWM drive conditions should not be interpreted as evidence of poor performance. It should be recognized as an unresolved area requiring direct measurement and comparision against established VFD cable constructions [1], [2], [19].

What changes is the cable architecture. MI cable does not use XLPE, EPR, PVC, foil, or braid in the way the usual VFD cable families do. It uses compacted magnesium oxide and a continuous copper sheath. That difference is large enough that conclusions from polymeric VFD cable research cannot simply be copied across. The sheath may be an excellent high- frequency containment feature. It may also alter capacitance and surge impedance in ways that affect reflected-wave behavior.

Both possibilities are credible. Neither should be asserted without data.

It would be easy to oversell MI cable because it is rugged inorganic, and metallic. That would be a mistake.

It would also be easy to dismiss it because it is not the default cable in existing VFD application guides. That would be lazy. The more defensible view is that MI cable occupies an under examined space between survivability engineering and drive system behavior.

Routine applications will usually remain better served by established VFD cable constructions. In higher-consequence applications, the design objective is broader. A smoke-control fan, high-temperature process motor, or fixed motor circuit in a contamination-sensitive area may justify cable selection that values environmental survivability as heavily as electrical convenience. In that setting, MI cable deserves to be tested rather than be ignored.

XI. CONCLUSION

Copper-sheathed mineral-insulated cable has a credible technical case for evaluation in selected VFD applications. The case is not that MI cable is automatically better than established VFD cable constructions. The case is that its combination of solid conductors, magnesium oxide insulation, and seamless copper sheath may offer value where a motor circuit must survive more than routine electrical duty.

Its strongest potential role is in fixed, harsh-environment, high-consequence, or survivability-driven installations: smoke control fans, emergency ventilation, elevated-temperature process areas, radiation-exposed zones, difficult-to-access loads, and other applications where the penalty for cable failure is unusually high. In those settings, a cable with a long record of physical and thermal resilience should not be excluded from the VFD discussion simply because the main body of published drive cable literature followed a different product path.

The electrical questions remain non-negotiable. MI cable should not be credited as a blanket cure for reflected-wave voltage, motor bearing currents, or PWM cable stress. Reflected wave behavior depends on characteristic impedance. Common mode current depends on capacitance, return-path impedance, and termination geometry. Bearing-current mitigation remains a system issue. Multicore and single-core MI arrangements should not be treated as the same electrical problem.

For routine motor circuits, the answer may still be an established shielded polymeric VFD cable or welded aluminum- sheathed MC cable. Copper-sheathed MI enters the decision only where survivability has real value and where measured ca- ble data confirm that the sheath, capacitance, surge impedance, and terminations do not create new VFD-side liabilities.

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