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MODERN POWER SUPPLY AUTOMATION SYSTEMS: TECHNOLOGIES, ADVANTAGES, AND DEVELOPMENT PROSPECTS

Summary. *Power supply automation technology rarely enters an industrial facility through a single, deliberate decision. More often it arrives piecemeal: a relay replaced after a failure, a communication standard adopted because a new switchgear supplier specified it, a storage unit purchased to solve an unrelated power-quality complaint. The result is that many facilities carry a mixture of automation generations without ever assessing that mixture as a whole. This paper takes stock of that situation. Drawing on twenty-five peer-reviewed sources published between 2018 and 2025, it surveys the technology available for automating power supply, from electromechanical protection and automatic reserve switching, known by its Russian-derived acronym ABP, through digitally coordinated substations built on IEC 61850, to self-healing distribution networks that integrate storage and demand-side resources into their own restoration logic. Rather than presenting these as a checklist of features to acquire, the paper argues that a facility's automation portfolio should be assessed as a coherent whole and proposes a five-level Power Supply Automation Maturity Model as a diagnostic tool* *for doing so. The model links each level to a distinct capital and operating profile, not only a technical one, so an upgrade decision can be weighed as an investment rather than a specification exercise. The paper closes by arguing that the more urgent question facing most industrial sites is not which new automation technology to buy, but which gaps in their existing, uneven portfolio actually justify closing first.*

Key words: *power supply automation; automatic reserve switching; ABP; substation automation; IEC 61850; self-healing distribution networks; energy storage; technology adoption.*

Introduction. Ask an electrical engineer at almost any industrial site what generation of protection and automation equipment the facility runs, and the honest answer is usually several generations at once. A rolling mill added twenty years ago may still rely on electromechanical relays and manually operated tie breakers, while a newer process line down the same yard runs microprocessor-based protection communicating over a digital bus that did not exist when the older equipment was specified. This unevenness is not evidence of neglect; it reflects how automation technology is actually adopted in practice, in response to equipment failures, vendor availability, and one-off projects, rather than through a single coherent plan.

That pattern matters because the individual technologies involved, automatic reserve switching among them, have matured considerably. Digital communication standards, chiefly IEC 61850, have turned the substation from a collection of independently wired devices into a coordinated system capable of making fast, network-wide decisions [2; 11]. Protection logic has moved from fixed timers toward adaptive, signal-based discrimination, in several cases assisted by machine learning [7; 9; 14; 19; 23; 24]. Distribution networks are increasingly designed to isolate a fault and restore supply automatically, treating distributed storage and even parked electric vehicles as flexible resources rather than passive equipment [12; 15;

16; 17; 18; 20; 22]. Each of these advances is well documented on its own terms. What is less well documented is how a facility should decide which of these advances is actually worth pursuing next, given that it is starting from an uneven baseline rather than a blank sheet.

This paper takes up that question directly. It reviews the automation literature not as a set of isolated technical contributions but as evidence of a technological progression, moving from a chronological account of that progression toward a practical model for assessing where a given facility sits within it. Section 2 traces this progression across the reviewed literature; Section 3 sets out the methodology used to convert that account into a usable model; Section 4 reports what the synthesis revealed; Section 5 presents the Power Supply Automation Maturity Model and works through how it applies to industrial and critical-infrastructure sites; Section 6 concludes.

Literature Review

1. The electromechanical and early digital baseline. Before considering where automation is heading, it is worth being precise about the baseline most facilities are still measured against. Escalera, Hayes, and Prodanovic surveyed the techniques used to assess reliability in distribution networks and found that the indices in common use were largely built for a passive, radially operated grid, an assumption that automated and distributed systems increasingly break [6]. That assumption is visible in practice at heavy industrial sites: Kornilov and colleagues, describing the power-supply arrangements at metallurgical iron-and-steel works, note that different process sections within a single plant can have sharply different tolerance for interruption, a distinction that a uniform, plant-wide protection philosophy tends to obscure [10]. Jooshaki and colleagues, working from the planning side, showed that distribution expansion under incentive-based reliability regulation can be formulated as a mixed-integer linear programme, treating reliability as a quantity optimized against cost rather than a fixed engineering target [8]. Adetokun and Muriithi added a further complication, reviewing flexible alternating current transmission system devices for voltage stability and showing that a switching event can itself destabilize voltage on a weak reserve source unless reactive power support is arranged in advance [1]. This literature suggests the electromechanical baseline was never quite as simple or uniform as commonly assumed, which matters for how any later automation upgrade should be evaluated.

2. The digitalization wave. The clearest technological discontinuity in the literature reviewed is the shift toward standardized digital communication within the substation. Aftab and colleagues traced how IEC 61850 replaced dedicated point-to-point wiring between protection devices with a shared communication bus, arguing that this shift, more than any single relay improvement, is what makes coordinated, fast decision-making across multiple protection zones practical [2]. Kumar, Abu-Siada, and colleagues reached a closely related conclusion, treating IEC 61850 adoption as the organizing event around which modern substation automation is now specified [11]. Altaf and colleagues complicated this picture by cataloguing protection difficulties specific to microgrids, where fault current can reverse direction depending on which source is active, a condition digital communication alone does not resolve without protection logic designed for variable topology [3]. Dagar, Gupta, and Niranjan reached a similar conclusion, arguing that schemes built for a passive, radial network frequently fail once a facility operates with parallel or alternating sources [5]. The digitalization wave also introduced a cost earlier, hardwired schemes did not carry: Ashraf and colleagues demonstrated that IEC 61850-based substations are vulnerable to denial-of-service attacks precisely because the communication layer enabling coordination is also an accessible attack surface, a finding that should temper any assumption that digital automation is an unqualified improvement over what it replaces [4].

Running alongside this digitalization is a parallel shift in protection philosophy, away from fixed-time logic and toward adaptive, signal-based decision-making. Han and colleagues developed a reclosing scheme that distinguishes a genuine fault from a transient using harmonic signatures in the secondary arc voltage, while Khan, Bi, and Jia surveyed the broader family of adaptive reclosing schemes built on similar logic for extra-high-voltage lines [7; 9]. Mehdi and colleagues extended this survey across AC, DC, and hybrid transmission technologies and concluded that adaptive, signal-based approaches outperform fixed-timer schemes consistently enough to be considered current state of practice [14]. More recent work applies machine learning directly to this decision problem: Saad, Kim, and Munir combined a particle filter with a convolutional neural network for single-phase reclosing, Xie and colleagues designed an adaptive scheme around a moving-average filter and quadrature signal generator for lines with shunt reactors, and Muzzammel and Raza applied a support vector machine to protection on multi-terminal HVDC systems, extending the same logic well beyond conventional AC networks [19; 23; 24]. Reclosing and reserve switching are formally distinct functions, but both depend on the same judgement, distinguishing a real, sustained disturbance from a transient one, which is why this work transfers so directly into the design of fast, adaptive ABP logic.

3. Toward autonomy: self-healing networks and integrated storage. The most recent phase visible in the literature moves automation from coordinated response toward autonomous restoration. Lu and colleagues proposed a self-healing scheme, built on mixed-integer linear programming, designed to restore supply quickly with minimal manual intervention following a fault [12]. Luo, Ge, and Xu supplied an important qualification, showing that the reliability actually delivered by such schemes is bounded by the quality of data transmission between distribution automation terminals rather than by the sophistication of the restoration algorithm alone [13]. Meteab and colleagues and Pang and colleagues each proposed their own self-healing frameworks, the former organized around efficient network-wide restoration and the latter around partitioning the network into manageable zones with flexible resource aggregation [15; 20]. Reiz, Pereira, and Leite proposed a further self-healing strategy aimed at modern distribution networks, while Mohammadi Hosseininejad and colleagues showed that self-healing performance can be enhanced by co-deploying automatic switches alongside electric vehicle parking lots, treating parked vehicles as a temporary, mobile reserve resource [18; 22].

Storage occupies an increasingly central place in this autonomous phase. Mohamad and Teh conducted a systematic review of how energy storage affects power system reliability, and a related review by Mohamad, Teh, Lai, and Chen traced the broader development of storage technology for network reliability purposes, together suggesting that storage is now designed into automation architecture from the outset rather than added afterward as a contingency [16; 17]. Yan and colleagues reviewed the methods used to assess the reliability of storage systems themselves, arguing that storage needs an assessment framework distinct from the one used for conventional generation [25]. Pavon and colleagues, examining optimal control strategies for smart grid substations, raised a concern that applies across this entire autonomous phase: transition stability, a substation's ability to move smoothly between operating states, is becoming as important a design criterion as its steady-state performance, and storage-integrated automation makes those transitions more frequent rather than less [21].

Taken together, this literature describes three overlapping technological eras rather than a single continuous improvement curve: an electromechanical baseline that is more heterogeneous than commonly assumed, a digitalization wave that brings coordination alongside new cyber risk, and an emerging autonomous phase built on adaptive logic and integrated storage. What none of this literature addresses directly is how a facility already straddling several of these eras at once should decide what to change next, which is the question this paper turns to now.

Methodology. This paper is built on a structured qualitative synthesis of twenty-five peer-reviewed journal and conference sources published between 2018 and 2025, covering substation automation, protection logic, reliability assessment, self-healing distribution, and energy storage. Rather than coding these sources against a fixed set of themes decided in advance, the sources were read chronologically by publication focus and organized into the three technological eras described in Section 2, electromechanical baseline, digitalization, and emerging autonomy, on the basis of which era's characteristic technology or concern each source primarily addressed. Each source was then coded a second time for three practical attributes: the switching or restoration time it reported or assumed, the communication or protocol dependency it required, and any capital or operating cost consideration it discussed explicitly, even in passing.

This second coding pass is what distinguishes the present synthesis from a straightforward literature summary and what feeds directly into the Power Supply Automation Maturity Model in Section 5. The technology boundaries between levels follow the eras identified in Section 2 [2; 11; 12; 15; 16; 17], while the operational account given by Kornilov and colleagues for metallurgical facilities was used to keep the lower levels of the model anchored in a real industrial setting rather than a purely theoretical progression [10]. The cybersecurity findings of Ashraf and colleagues were carried through as an explicit cost and risk consideration attached to the higher, digitally coordinated levels, rather than treated as a separate technical footnote [4]. The resulting model is a conceptual planning tool built entirely from published sources rather than site-specific measurement or cost data; no proprietary or unpublished information was used, and every claim in this paper traces back to one of the twenty-five sources in the reference list.

Results. Five observations emerged from the synthesis and are carried into the discussion that follows.

First, the reviewed literature does not describe a single automation frontier that all facilities are converging toward; it describes three overlapping eras, and most real facilities occupy more than one simultaneously, a pattern the literature acknowledges implicitly through its own uneven treatment of baseline heterogeneity, digitalization, and autonomy [6; 8; 10]. Second, the digitalization wave delivers its coordination benefits and its cybersecurity exposure as a package, not as separable options, meaning that a facility cannot reasonably adopt the communication benefits of IEC 61850 while deferring the governance obligations that come with it [2; 4; 11]. Third, adaptive and machine-learning-assisted protection logic has matured to the point where it now outperforms fixed-timer schemes across a wide range of protection functions, not only reclosing, suggesting that this logic is better understood as a general capability than as a feature specific to any one protection application [7; 9; 14; 19; 23; 24]. Fourth, the reliability gains claimed for self-healing and autonomous restoration schemes are conditional on communication infrastructure quality in a way the underlying algorithms cannot compensate for, which means the case for moving toward autonomy rests as much on a facility's telecommunications position as on its appetite for new switching logic [13]. Fifth, storage is shifting from a contingency asset toward a design input for automation architecture, and this shift changes the underlying economics of automation upgrades, since a storage investment can substitute for, rather than simply complement, certain classes of switching decision [16; 17; 25].

Taken together, these findings point toward a conclusion that is easy to state but not straightforward to act on: the technology exists to build a highly capable, largely autonomous power supply automation architecture, but almost no facility is starting from the same baseline, and the literature offers little guidance on how to sequence an upgrade path given that starting point. That sequencing problem, treated as a diagnostic and investment question rather than a purely technical one, is the focus of the discussion below.

1. Assessing a portfolio rather than choosing a technology. The central difficulty this paper has tried to surface is that most industrial facilities are not choosing among competing automation technologies from a blank slate; they are managing a portfolio of equipment purchased at different times, for different reasons that now needs to be assessed as a whole. Framed this way, the relevant question shifts from which technology performs best in isolation, a question Section 2 answers reasonably well, to where the gaps in an existing, uneven portfolio actually justify investment. Kornilov and colleagues make this concrete: within a single metallurgical facility, some process sections may already warrant fast, adaptive protection while others are adequately served by conventional switching, and a plant-wide policy that ignores this variation will misallocate investment in both directions [10].

2. The Power Supply Automation Maturity Model. This paper proposes a five-level Power Supply Automation Maturity Model, summarized in Table 1, as a diagnostic tool for this portfolio assessment. Level 0 corresponds to manual and electromechanical control, still standard practice at facilities such as the metallurgical works described by Kornilov and colleagues, where switching decisions rely on fixed-time relays and local operator judgement [10]. Level 1 introduces microprocessor-based digital relays and standard automatic reserve switching, adding configurable logic and diagnostics without yet requiring a shared communication bus. Level 2 corresponds to the digitalization wave described in Section 2.2, built on IEC 61850 and requiring the cybersecurity governance that Ashraf and colleagues show is inseparable from its coordination benefits [2; 4; 11]. Level 3 layers adaptive, signal-based, and in some cases machine-learning-assisted protection logic onto that digital foundation [7; 9; 14; 19; 23; 24]. Level 4 corresponds to the emerging autonomous phase, a self-healing, storage-integrated architecture in which faults are isolated and supply restored across a wider network with minimal operator involvement [12; 15; 16; 17; 18; 20; 22] (See Figure 1).

Table 1

Proposed Power Supply Automation Maturity Model (PSAMM)

Level	Description	Enabling technologies	Typical reliability outcome	Key references
0	Manual and electromechanical control	Fixed-time relays, manual switching, local operator judgement	Multi-second to minutes-scale interruption; recovery depends on operator response	[10]
1	Microprocessor-based digital relays with standard ABP	Configurable digital relay logic; point-to-point wiring	Switching in roughly 0.3 s to 1.5 s; improved diagnostics	[10]
2	IEC 61850-based digital substation automation	Shared digital communication bus; coordinated multi-bay protection	Faster, coordinated switching; new cybersecurity exposure	[2; 4; 11]
3	Adaptive, signal-based protection and switching logic	Signal-based fault discrimination; machine-learning-assisted decision logic	Sub-second, adaptive discrimination between genuine faults and transients	[7; 9; 14; 19; 23; 24]
4	Self-healing, storage-integrated architecture	Network-wide automated restoration; distributed storage and flexible resources (including EVs)	Automatic fault isolation and supply restoration across the network	[12; 15; 16; 17; 18; 20; 22]

Source: developed by the author

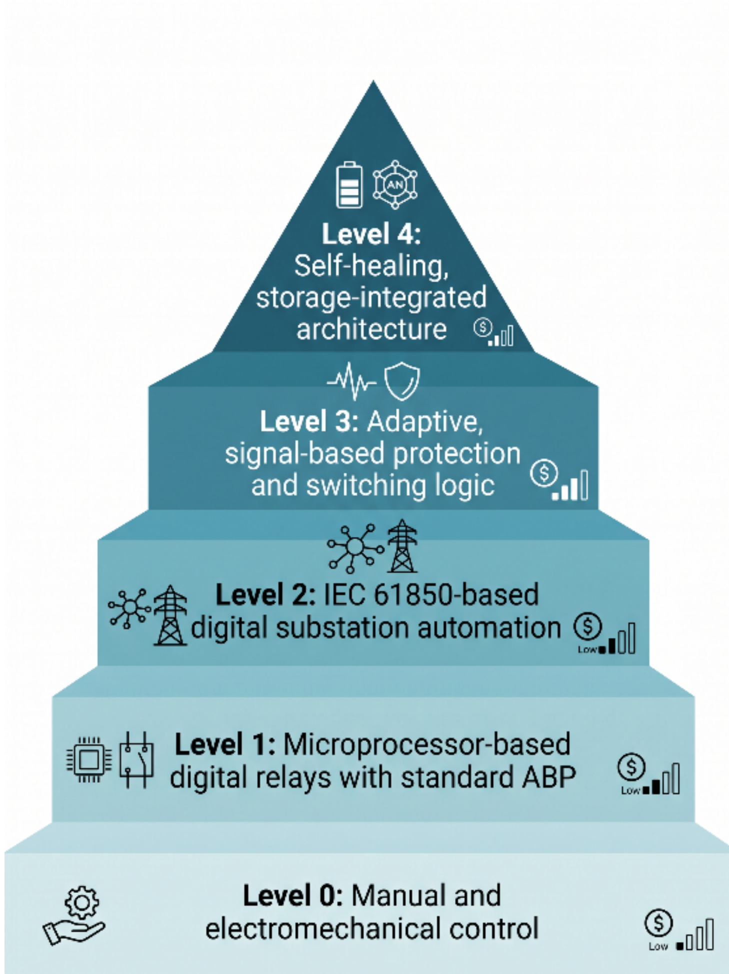

Fig. 1. Power Supply Automation Maturity Model Infographic

Source: developed by the author

The distinguishing feature of this model, relative to treating each technology as a standalone upgrade, is Table 2, which attaches a characteristic facility profile and cost signal to each level rather than only a technical description. A Level 1 facility typically carries low ongoing communication cost but limited coordination across process areas; a Level 2 facility takes on new recurring cybersecurity governance cost in exchange for that coordination; a Level 3 facility requires investment in signal-processing or analytics capability that a Level 2 facility does not; and a Level 4 facility requires the largest upfront capital commitment, chiefly in storage and communication infrastructure, but is the only level at which storage can begin substituting for, rather than merely supplementing, certain switching decisions [16; 17; 25] (See Figure 2).

Table 2

Characteristic cost profile and distinguishing capability by maturity level

Level	Characteristic cost / investment profile	Distinguishing capability gained
1	Low recurring communication cost; limited coordination across process areas	Configurable relay logic and improved diagnostics
2	New recurring cybersecurity governance cost taken on in exchange for coordination	Coordinated, multi-bay protection over a shared digital bus [4]
3	Investment in signal-processing or analytics capability beyond Level 2	Adaptive discrimination of genuine faults from transients
4	Largest upfront capital commitment, chiefly storage and communication infrastructure	Storage begins substituting for, rather than merely supplementing, certain switching decisions [16; 17]

Source: developed by the author

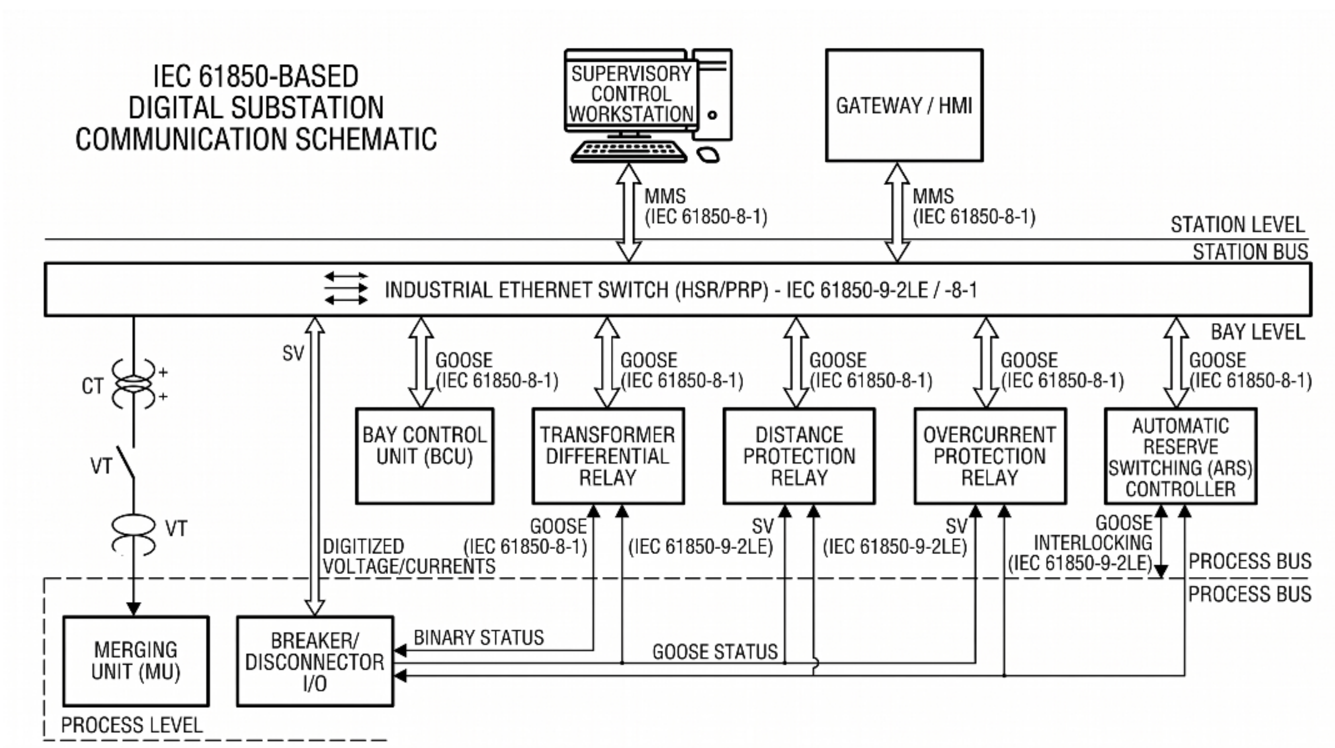

Fig. 2. IEC 61850 Digital Substation Schematic with GOOSE Messaging

Source: developed by the author

3. What this means for industrial and critical-infrastructure sites. For a facility resembling the metallurgical case described by Kornilov and colleagues, the model suggests a targeted rather than uniform response: raising only the most interruption-sensitive process sections to Level 2 or Level 3, while leaving auxiliary loads at Level 1, is likely to deliver more reliability per unit of investment than a single plant-wide upgrade [3; 5; 10]. Critical infrastructure operators that already maintain a distribution automation footprint are better positioned to consider Level 4, but only if the communication-quality concerns raised by Luo, Ge, and Xu are addressed as a precondition rather than an afterthought [13]. The model also reframes the role of storage: a facility does not need to reach Level 4 to benefit from it, since the literature reviewed in Section 2.3 shows storage delivering measurable reliability value well before a full self-healing architecture is in place [16; 17; 25] (See Figure 3).

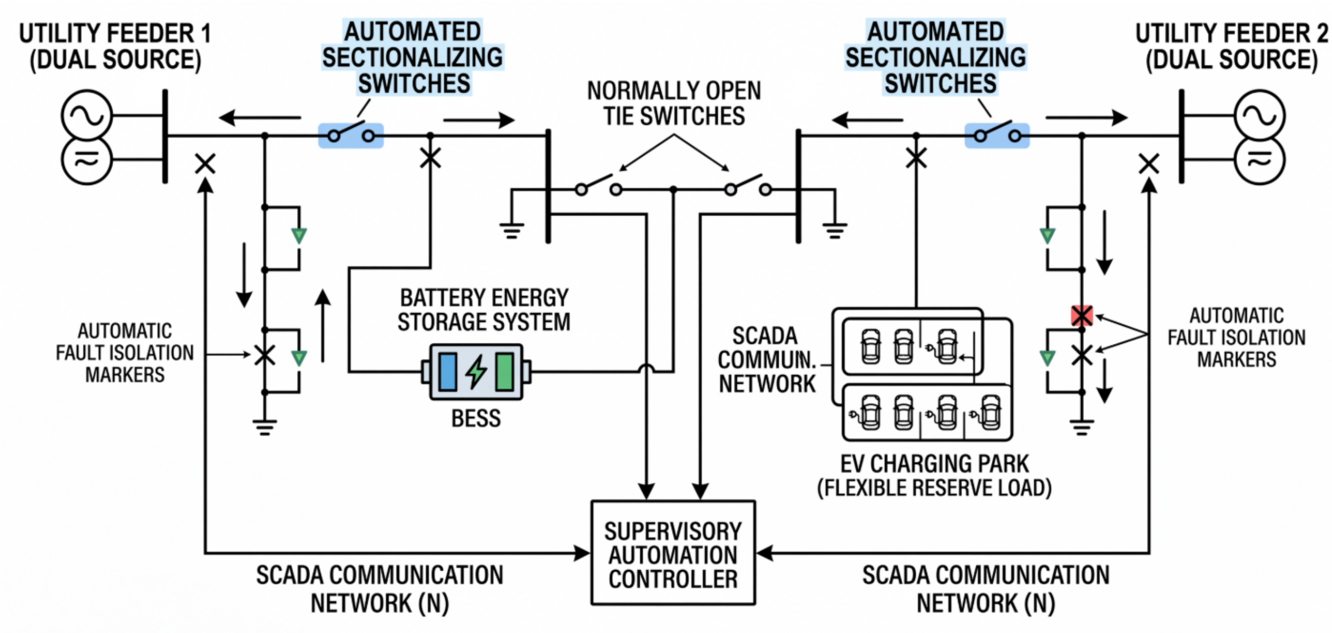

Fig. 3. Self-Healing Smart Distribution Grid

Source: developed by the author

4. Limitations and directions for further work. This model was built entirely from published technical and cost signals rather than from site-specific interruption-cost or capital-expenditure data, and testing the proposed level boundaries against real transition data at facilities moving between levels is the most pressing next step. The optimization approach that Jooshaki and colleagues applied to distribution expansion planning under reliability regulation offers a workable template for turning the level-selection decision proposed here into a formal constrained-optimization problem rather than a qualitative judgement call [8]. The transition-stability concerns raised by Pavon and colleagues also merit closer attention in any staged upgrade plan, since a facility moving between levels is, almost by definition, spending more time than usual in transitional operating states that this model does not yet characterize in detail [21].

Conclusions. Most industrial facilities are not deciding whether to adopt power supply automation; they already have, unevenly, over years of piecemeal investment. The more useful question, and the one this paper has tried to answer, is how such a facility should assess the portfolio it already has and decide where the next investment actually belongs. The literature reviewed here documents a clear technological progression, from electromechanical baseline through digital coordination to adaptive, largely autonomous restoration, but offers comparatively little guidance on sequencing that progression for a facility that is not starting from zero. The Power Supply Automation Maturity Model proposed in this paper addresses that gap by attaching a concrete technical and cost profile to each stage, allowing a facility to locate itself honestly and weigh the next step as an investment decision rather than a specification exercise. Automatic reserve switching remains the anchor of this progression throughout, not because it is superseded by later stages but because every later stage depends on it working correctly. Confirming the practical value of the proposed levels against real transition and cost data at operating facilities is the logical next step for this line of work.

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